NBSIR 83-2694

Some Criteria for Colors and Signs in Workplaces

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Physics Division
Washington, DC 20234

April 1983

Sponsored by

**The Occupational Safety and Health Administration
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SOME CRITERIA FOR COLORS AND SIGNS IN WORKPLACES

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

The use of safety-related visual displays such as signs and colors in workplaces is discussed. The discussion includes a review of relevant national and international standards for safety colors and signs. It also includes a review of measures of spatial resolution in human vision, as well as of color sensitivity and color appearance. In addition, research on the effectiveness of safety signs, symbols, and colors is reviewed. Based on the initial literature review, the appearance of safety colors under energy-efficient light sources was identified as an area for detailed research. As a result, a laboratory study was conducted in which the color appearance of 45 different color samples under five light sources including energy efficient ones was determined for seven subjects. The color samples were contained in four color series: standard safety colors; experimental colors; retroreflective and retroreflective-fluorescent colors; and fluorescent-only colors. The results indicated the existence of a set of colors which was more identifiable under all light sources than the current standard safety colors. This set contains a number of fluorescent and retroreflective colors, unlike the current safety colors. Recommendations are made for further research, including field research, to determine the effectiveness of the suggested color set on safety signs under an even broader range of illuminants. The need to assess color appearance under mixed light sources is also addressed.

Keywords: Chromaticity, color, color appearance, energy-efficient lights, illumination, light source, safety, safety signs, safety symbols, visual acuity, visual sensitivity.

FOREWORD

This report is one of a series documenting the results of NBS research in support of the Occupational Safety and Health Administration (OSHA), in fulfillment of OSHA contract No. 1AG No. J-9-F-7-0146 entitled "Criteria for Signage in Workplaces." The report summarizes research conducted in the period December 1977 through April 1983.

We wish to acknowledge with special thanks the interest, cooperation, and encouragement of the sponsor's Technical Project Officer, Mr. Tom Seymour, OSHA Office of Standards Development.

DISCLAIMER

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1. INTRODUCTION

1.1 BACKGROUND

Warnings and other safety-related messages are typically communicated by visual displays, both within fixed workplaces and around temporary work sites, indoors and outdoors. Safety-related visual displays usually perform two functions: alerting personnel to the presence of some situation requiring their attention; and tranmitting further information concerning the nature of this situation and/or the action to be taken by the viewer. A visual display may be used to communicate information by means of various components such as color, overall shape, verbal legends, and non-verbal graphic symbols. To accomplish the two basic goals, the overall display (color and shape) should be as attention-attracting as possible. Furthermore, the elements carrying the specific information (legends and symbols) should be as concise, unambiguous, and understandable as possible, and should be visible at the appropriate viewing distance.

Although requirements and standards for visual displays, including warning signs, have been in existence for a long time, the research base for these recommendations is sometimes inadequate. In particular, the use of energy-efficient light sources, such as high- and low-pressure sodium can distort color noticeably, thus reducing the effectiveness of color coding in safety displays or signs.

The present report will outline some requirements for effective signs and present some preliminary data on the recognizability of safety colors under different light sources, including several energy efficient sources.

1.2 EXISTING STANDARDS

The Occupational Safety and Health Act of 1970 had two sections dealing with safety colors, signs, and tags. Section 1910.144, The Code of Federal Regulations (CFR), 29, Labor, Part 1910.144, contained a Safety Color Code for Marking Physical Hazards, while Part 1910.145, contained Specifications for Accident Prevention Signs and Tags. Some of these recommendations have since been partially deleted (Code of Federal Regulations, 29, 1981), although the regulations still provide general sign and color requirements for safety. (Part 1926.200, Subpart G provides specifications for signs, signals, and barricades for the construction industry.) The Occupational Safety and Health Administration (OSHA) (Code of Federal Regulations, 29, 1981, p. 360) defines a (safety) sign as a surface "prepared for the warning of, or safety instructions of, industrial workers or members of the public who may be exposed to hazards. Excluded from this definition, however, are news releases, displays commonly known as safety posters, and bulletins used for employee education". Existing OSHA requirements are summarized in table 1. The development of any new performance-based standards or guidelines requires research on the effectiveness of safety colors and signs under a variety of illuminants including the energy efficient light sources. This need is addressed in the present report.

Table 1. OSHA Sign Requirements--1910.144, 1981

COLOR	MEANING	APPLICATION
Red	Danger	Safety cans Portable cans with flammable liquids Barricades
	Stop	Emergency stop buttons or switches
Yellow	Caution	Designate caution Mark physical hazards

TYPE	SIGNS	COLORS
Danger	Indicate presence of immediate hazards;	Red, black, and white
	Caution against unsafe practices	Yellow and black
Safety instructions	Indicate general instructions and suggestions relative to safety messages	White and green
Slow Moving Vehicles	Unique identification for vehicles which by design move slowly on public roads	Fluorescent yellow-orange with dark-red border
Biological Hazard	Signify actual or potential presence of a biohazard; identify equipment, container rooms, materials, experimental animals which contain or are contaminated with viable hazardous agents	

OSHA's interest is not confined to the Occupational Safety and Health Standards mentioned above, however. At this time, there are over one hundred other requirements in the General Industry Standards for signs, markings, or other color/legend associations. Yet, there is no requirement for adherence to a widely accepted safety sign or color standard, nor are there any methods for measuring compliance.

Three basic problems exist in the consideration of color/legend standards today:

1. There is a growing proliferation of requirements at the international, federal, and state levels, as well as at the voluntary standards level, addressing different aspects of the color/legend problem.

2. There is often a lack of experimental research to support the criteria for these requirements.

3. There are no formalized procedures for measuring compliance with the requirements.

1.2.1 Proliferation of Standards

Over the years, various agencies and groups evolved practices and standards for safety-related visual displays. These guidelines include specifications for color, shape, word legend, and symbols. Although some features are common to the various systems, such as the use of red to indicate "danger" or "stop", the systems are not necessarily consistent. The result is the repeated exposure of the population to signs and displays which follow contradictory conventions, thus resulting in confusion and possible danger. Consequently, the user cannot attach any single, invariant meaning to colors, shapes, or symbols used in the visual displays encountered every day. The adoption of a single, unified system would allow more rapid and more certain recognizability of the meanings of visual displays and thereby contribute to the safety of both workers and the general population.

To complicate matters further, both the American National Standards Institute, ANSI, and the International Organization for Standardization, ISO, have drafted voluntary standards for safety signs and displays. The ANSI Z35.1 (1972) Standard provides specifications for safety signs while the Z53.1 (1979) Standard provides specifications for safety colors to be used on these safety signs. The ANSI Z35 and Z53 committees have recently been combined to form the Z535 Committee on Safety Signs and Colors. This committee is currently updating the Z53 (Color) Standard, and the Z35 (Sign) Standard, and will issue them as the Z535.1 (Color) and Z535.2 (Sign) standards. This committee is also drafting Standards for Safety Symbols (Z535.3) and Product Alerting Signs (Z535.4). Within the ANSI Z35 (1979) framework, the following conventions regarding color were specified: Red = danger, stop; Yellow = caution; Green = location of first aid, safety; Blue = general information. A third hazard category is proposed in current Z535.2 and Z535.4 drafts which would use Orange for warning. These provisions are outlined in table 2.

Table 2. Coding Practices from International and U.S. Safety Sign Standards

	ISO/EEC	CANADIAN	U.S.*
Red	Prohibition	Prohibition, Danger	o Danger o Stop o Fire & Emergency
Orange	----	----	o Dangerous Machine o Energized Equipment o Warning - Proposed
Yellow	Warning	Caution	o Caution - Storage for Flammables o Containers for Explosives, or Unstable Materials - Radiation o Highway
Green	Information	Emergency Information	o Safety Information o First Aid & Safety Equip. o Highway - square, rect.
Blue	Mandatory Action	Miscellaneous	o Information o Bulletin Boards o Railroad
Black		Mandatory Action	

* Adopted from ANSI Z35 and DoT (1971).

The ISO TC-80 on Safety Signs and Colors developed a draft standard (1978) which specifies color and symbol sign configuration. These provisions are also summarized in table 2. It is immediately apparent from inspection of table 2 that the ANSI and OSHA standards use color to code the level of hazard, with red for danger and yellow for caution, while ISO uses only yellow to code the presence of a hazard. Red is reserved for prohibition. Both set of standards agree on the use of green for safety and blue for general informational signs, although ISO specifically identifies a "mandatory action" category, using blue to code information such as "personal protective gear required." The Canadian Treasury Board Standard (1980), however, uses black for this latter category. In addition, the ANSI Z35 Standard relies upon word messages to communicate hazard warnings while the TC 80 Standard uses symbols exclusively.

1.2.2 Decision Criteria for Improving Visual Alerting Systems

The proliferation of existing standards emphasizes the need to develop a research base for decisions about effective visual alerting displays for safety. Although numerous research studies on coding and visual displays have been completed, they have not been applied to the use of safety signs in workplaces. In some cases, such as new applications of energy-efficient light sources, the research base itself is minimal.

There is, consequently, a great need to develop criteria for safety signs and displays. These criteria should address the following ideas:

a) Color selection, under normal and adverse conditions, including various types of artificial lighting, such as metal halide, sodium, mercury, and fluorescent. The high intensity discharge sources, which can have poor color rendering characteristics, are gaining wide use in industrial settings due to their lower operating costs.

b) The use of retroreflective or fluorescent colors.

c) The readability of the display and the appropriate viewing distance.

d) The durability of the display.

e) Symbol recognition, legibility, and conspicuity.

f) Characteristics of luminous displays, including intensity, flash rate, color, etc.

g) Human visual sensitivity, including color deficiencies and other handicaps.

1.2.3 Measurement of Compliance

Although color/legend requirements are liberally sprinkled through OSHA (and other Federal agency) regulations and standards, there are few specifications for determining compliance. Is the color the correct hue, value, and chroma?

Is the light source intensity adequate, and the right spectral distribution for maximizing the legibility of the signs? Is the viewing distance and height adequate? Is the sign size adequate for the conditions? Does the sign provide the information necessary for employee safety? Answers to these and other questions are needed to provide a scientific basis for specifying requirements for any new standards or guidelines for safety and hazard markings, as well as for determining compliance procedures.

The present report addresses the general topic of visual requirements for safety, with a focus upon sign color and legibility, particularly under different illuminants. It presents the results from a study on safety color appearance under five different light sources, including data on the recognizability of retroreflective and fluorescent colors, and provides some recommendations for sign and color applications in workplaces.

2. VISUAL REQUIREMENTS FOR SAFETY COMMUNICATION

2.1 BACKGROUND

A worker who moves around an industrial facility must be constantly aware of potential hazards in this environment. In general, there are three stages in the perception and reaction of people to workplace hazards. These include:

1) Awareness of the hazard
2) Recognition of the nature of the hazard
3) Response to the hazard.

Usually (but not always) stage 1 requires performance of a visual task by the employee. The most common visual task is the location and identification of a safety or warning sign (in addition to locating and identifying a potential hazard). Therefore, to alert a person to a potential hazard or safety message, one should locate a safety sign such that it: 1) attracts the attention of the person; 2) conveys information about the hazard; and 3) is located so that the person can respond in a timely and appropriate fashion (Chaffin, Miodonski, Stobbe, Boydstun, and Armstrong, 1978).

The ability of a sign to attract the attention of the worker assumes that the sign is VISIBLE. The question of sign visibility requires information about at least four sets of variables: the visual performance abilities of the observer, characteristics of the visual stimulus (or sign), characteristics of the illumination system, and optical properties of the atmosphere. The observer capabilities include: observer acuity, adaptation state, age, opacity of the lens and cornea, color deficiencies, and chromatic adaptation. Sign visibility requires knowledge of both the illumination system characteristics and those of the sign or visual stimulus. These include: illumination level, type and spectral characteristics of the illumination; as well as characteristics of the sign such as size, shape, contrast, color, location, size of letters and symbols, stroke width, stroke width-to-height ratio, legibility, and cleanness. The fourth set of variables includes those related to the optical transmission properties of the atmosphere within the line of sight, including haze, smoke, dirt, dust, or pollution.

In the present paper, the focus will be upon the visual performance of the observer and the properties of the visual stimulus and the illuminant. The reader is referred to Middleton (1963) and Douglas and Booker (1977) for a further discussion of the optical properties of the atmosphere, and to Howett, Kelly, and Pierce (1978) for a discussion of the use of flashing lights as warning devices. Visual performance of the observer will be discussed primarily in terms of spatial resolution including measures of acuity and contrast, and chromatic sensitivity. Similarly the properties of the visual stimulus will be addressed in terms of legibility and color. The illumination system will be discussed in terms of spectral transmission, color temperature, and potential color rendering capabilities.

2.2 MEASURES OF SPATIAL RESOLUTION IN HUMAN VISION

What type of detail can the human eye resolve in near and distant viewing situations? Although a person's ability to resolve detail can be altered by either near or far-sightedness, as well as by disease, some measures of general human visual acuity under "normal" viewing conditions may be summarized. The reader is referred to Thomas (1975) for a fuller discussion of these issues.

2.2.1 Specific Variables

Visual acuity, or the resolving power of the eye, is defined in terms of the smallest detail that the eye can resolve. The stimulus used to test acuity is usually either a black pattern on a white background or the reverse. In either case, lightness contrast is made as great as possible. The size of the test pattern is systematically reduced until the critical feature is just barely resolvable. The acuity threshold is then stated in terms of the angle subtended at the eye by the threshold critical feature. Visual acuity is defined as the reciprocal of the threshold, when the threshold is specified in terms of minutes of arc. Normal acuity is 1.0, corresponding to a pattern that is just barely resolvable and whose critical dimension subtends 1 minute of arc at the eye. Thomas (1975, p. 234) says "In Snellen notation, acuity is expressed as the ratio of the distance in feet at which a detail is resolved to the distance at which the detail would subtend 1 minute of arc. Thus, 20/10 indicates that a detail that is just resolved at 20 feet would subtend 1 minute of arc if viewed from 10 feet. The equivalent decimal acuity is 2.0." There are a variety of test patterns which are used to measure acuity. In general, the test pattern may be one of the six following types.

2.2.1.1 Minimum Distinguishable

What is the smallest point, line, or other shape that can be recognized on a contrasting field? Hecht and Mintz (1939) showed that when conditions are optimized, a threshold width of 0.5 seconds of arc was obtainable for a long dark line on a very bright background. This is more than two orders of magnitude (120 times) smaller than the traditional one-minute-of-arc acuity threshold, and was made possible by the great length of the line, and even more by the extreme contrast obtainable with an opaque object viewed against a self-luminous background. Much lower contrasts are achievable on painted signs, and the threshold in such a "real-world" situation is considerably larger.

2.2.1.2 Minimum Separable

This task is usually tested with two dark points or lines whose distance apart is gradually changed. The smallest distance between the two targets in which they are resolved individually is the measure of interest. Craik (1939) found that under ideal conditions, 0.5 minute of arc was the minimum separable gap that was resolvable.

2.2.1.3 Vernier Acuity

Vernier acuity may be defined as the ability to discriminate the break between two end-to-end lines that are slightly displaced laterally. Berry (1948) showed that such thresholds range down to 1 to 2 seconds of arc. Vernier acuity is not usually relevant to sign visibility.

2.2.1.4 Minimum Recognizable

This measure of visual acuity applies to the recognition of distinct shapes such as Landolt rings or Snellen letters. A Landolt ring consists of a black circle with one gap located at varying positions, similar to a letter "C". The ring is varied in size, maintaining strict proportions, to find the smallest gap that can be seen. Snellen letters are alphabetic characters which are reduced in size until they are barely legible. Threshold for this task (minimum recognizable) is based on stroke width, length of the letter arms, and width of gap between arms (Sloan, 1951).

2.2.1.5 Contrast Sensitivity

Another way of assessing the resolving power of the visual system, is by determining the minimum contrast needed to see a grating pattern (Schade, 1956). The word "grating" refers to a pattern of alternating light and dark bars. By reducing the difference in luminance between the light and dark bars, a "contrast" threshold may be obtained. The reciprocal of threshold is termed "contrast sensitivity". One common definition of contrast particularly as applied to gratings is the following:

$$C = (L\ max - L\ min) / (L\ max + L\ min)$$

where:

C = contrast
L max = luminance of bright bars
L min = luminance of dark bars

This definition of contrast is also referred to as "modulation".

The number of light and dark bars (cycles) per degree of visual angle describes the fineness of the grating. Campbell and Robson (1968) provided illustrative data showing the contrast sensitivity versus spatial frequency for square and sine-wave gratings at two luminance levels.

2.2.2 Variables Affecting Resolution

The variables which affect a person's ability to resolve detail can be divided roughly into six categories: illumination level (luminance), retinal location, pupil size, spectral composition of the illuminant, orientation, and viewing distance. The effect of these different variables will be discussed to determine their impact on visual resolution.

2.2.2.1 Illumination Level

Acuity in general depends on the luminance of the background against which the dark target is seen (or the target luminance, if it is the background that is dark). In the practical case of reflecting signs, the dark portions of the display have measurable luminance, and that luminance is also relevant. Generally, acuity increases with illumination level and is better at photopic, rather than scotopic levels of illuminantion. The photopic luminance range begins at about 1 footlambert (fl), with good color discrimination occuring at levels above this.

2.2.2.2 Retinal Location

Many researchers (Ludvigh, 1941; Mandelbaum and Sloan, 1947; Sloan, 1968) have shown that acuity is optimal when the target is viewed by the central fovea of the eye. In the periphery, acuity increases slowly as the intensity of the illumination is increased. Under semi-dark (scotopic) conditions, when the rods mediate resolution, acuity is highest for targets at 4 degrees eccentricity (4 degrees from the central fovea, Mandelbaum and Sloan, 1947). Apparently, there is little relation between the distribution of the rods and scotopic acuity, as the greatest concentration of the rods is at about 20 degrees eccentricity. Maximum scotopic acuity may be as much as 10 times less than maximum photopic acuity, however (Brown, 1965).

2.2.2.3 Spectral Composition of Illumination

Of interest to visual safety requirements is the question of visual acuity under narrow-band versus broad-band illuminants. This question does not appear to be easily answered, since it appears to depend upon which measure of acuity is used. Narrow band illumination reduces chromatic aberration and might be expected to yield higher acuities. Shlaer, Smith, and Chase (1942) found improvements with monochromatic illumination when the measure was minimum visible acuity, while Baker (1949) found improvements when the measure was vernier acuity. However, Shlaer et al. (1942) found no difference between acuities measured in narrow-band and wide-band illumination for the Landolt ring measure of visual acuity.

Does acuity depend on particular wavelengths when narrow band illumination is used? According to Thomas (1975), if higher intensities are used, where acuity no longer varies as a function of intensity, and assuming a moderate pupil diameter, acuity does not appear to vary as a function of wavelength. (For very small pupils, where diffraction becomes the limiting factor, acuity appears to be higher for short wavelength illumination than for longer wavelength illumination.)

2.2.2.4 Orientation

Lines or striations that are oriented vertically or horizontally are seen better than lines which are oblique (Ogilvie and Taylor, 1958; Higgins and Stultz, 1948; Shlaer, 1937; Campbell, Kulikowski and Levison, 1966; and Watanabe, Mori, Nagata, and Hiwatashi, 1968).

2.2.2.5 Viewing Distance

As the viewing distance of the target changes, the lens of the eye changes shape, or accommodates, in order to focus on the target. In general, all eyes have a near point limit, such that signs or objects presented closer than the "near-point" cannot be brought into sharp focus. As a person ages, the eye steadily loses its ability to focus for near work; in other words, the near point recedes. In most people, the need for bifocals or reading glasses to overcome this loss is felt about age 40 to 50. Myopic (near sighted) eyes also have a "far point" focus for which targets presented beyond this point cannot be sharply resolved. Acuity suffers if the target is outside this resolvable range.

The reader is referred to Howett (1983) for a more complete discussion of a methodology for calculating legibility from visual acuity. Suffice it to say for the present paper, that Smith (1979) recommends a minimum letter height for 100 percent legibility of about 0.84 in. for a viewing distance of 10 ft and 2.1 in. height at 25 ft, or a letter height which subtends about 10 to 24 minutes of arc. No comparable recommendations exist for symbol size. The Howett paper provides a means of calculating letter size for observers with different visual acuities.

2.3 COLOR SENSITIVITY AND COLOR CODING

The ability of the human eye and brain to distinguish the color of objects is known as color vision (or chromatic visual perception). Not all people have normal color vision and the specification of safety colors should take this fact into consideration. Color vision defects will be discussed further in section 2.3.1.

The International Labour Office (1972, p. 323) states that: "From the point of view of occupational safety, colour vision is of great importance as many accidents are caused by lack of suitable lighting or by failure on the part of a worker to identify conventional identification colours, such as on electric cables, gas cylinders, pipelines, guide marks, control buttons of machines, safety devices, and limit signals."

The concept of the color of an object is not as simple as it might appear at first. In general terms, the color appearance of an object depends on three main variables:

A. The visual sensitivity of the observer at the moment the object is viewed;

B. The spectral reflectance (or transmittance) distribution of the object, dependent on the particular pigments or dyes that give the object its color; and

C. The type of illumination under which the object is viewed.

2.3.1 Color Sensitivity

Human visual sensitivity is mediated by two primary types of photoreceptors, the rods and the cones. The rods, which are located outside the center of the eye (central fovea) are extremely sensitive to light, being capable of detecting the presence of only one or two quanta of light (Cornsweet, 1970). They are, however, insensitive to color. The cones, on the other hand, are maximally sensitive to color and color differences. There are three cone pigments, with maximal sensitivities occurring at about 450 nm, 530 nm, and 560 nm (Hurvich, 1981).

In the United States (and Europe) about 8 to 10 percent of adult males (caucasian) and 0.5 percent of adult females (caucasian) are color defective, with variations in these percentages depending on the ethnic population studied (Rubin and Walls, 1969; Krill, 1972). There does appear to be some variation in the incidence of color defects in different countries and different ethnic populations, although such variation will not be discussed in detail here. Such persons may simply be missing one or more of the three photopigments, or they may possess an anomalous pigment. Thus, dichromatic observers have only two pigments, while a cone monochromat (extremely rare) only has one. A rod monochromat, also an extremely rare individual, has only the rod mechanism active so that both visual acuity and color sensitivity are drastically reduced (Hecht, Shlaer, Smith, Haig, and Peskin, 1948). The various dichromatic deficiencies are of particular concern in the workplace, however. Commonly occurring dichromatic defects are related to the absence of the red photopigment (protanopia) or the absence of the green photopigment (deuteranopia) (Vos and Walraven, 1970). The third, much rarer, type, tritanopia, is related to the absence of the blue photopigment. In addition to the loss of photopigments, another class of color defects--the most common type--is the anomaly, in which the person is still trichromatic, but the spectral sensitivity of one photopigment is shifted from the normal. Persons with these anomalies will perceive colors somewhat differently from the normal and discriminate colors somewhat more poorly.

Both protonomalous and deuteranomalous defects are generally more common than the comparable dichromatic defect (Rubin and Walls, 1969). Rubin and Walls (1969) give the following breakdown for the estimated 8.8 percent of the male population that is believed to be color deficient: 5 percent deuteranomaly; 1.3 percent protanomaly; 0.0001 percent tritanomaly; 1.2 percent protanopia; 1.3 percent deuteranopia; and 0.0001 percent tritanopia. Although tritanopic defects are extremely rare, (and occur equally among males and females), acquired color defects in which sensitivity to blue is lost (due to injury or disease) are more common. In addition, as one ages, one's lens and cornea yellow, thus reducing sensitivity to blue. Eye diseases such as cataracts and glaucoma also reduce sensitivity to blue. Lakowski (1969) estimated the percentage of acquired color defects to be about 5 percent of the population.

The practical effect of color deficiency is to cause observers to make abnormal color matches or confusions between colors. Because both major types of defects--protan (including protanopia and protanomally) and deutan (including deuteranopia and deuteranomally)--are concentrated in the red and green,

confusions between these colors must be carefully considered. Blue-yellow confusions are rare, so that it is not economically practical to make any allowance for them in designing color codes. Work cited by Judd (1948) suggested that a red should be somewhat orange, while a green should be somewhat blue to reduce confusions by protans and deutans. The current standard colors for traffic light signals reflect this concern.

Dichromats, unlike trichromats, only require two primary colors to match any third color. As a result, they will see as identical entire ranges of colors that appear quite distinct to a trichromat (see figure 1). For example, protanopes (figure 1a) confuse reds and bluish-greens, deuteranopes (figure 1b) confuse purples with pure greenish-blues, and tritanopes (figure 1c) confuse blues and greens. Both full-fledged protanopes and deuteranopes appear to lack totally the perceptions that color-normal observers term red and green; they see the world only in blues and yellows (Judd, 1948, 1949). (This conclusion can never be certain, but is widely accepted as highly probable.) Tritanopes appear to have better overall color discrimination with defects in wavelength discrimination emerging only in the blue-green region (Smith, 1973). They are believed to see the world entirely in reds and greens. (It should be noted that color defective observers often can distinguish colors on the basis of luminance cues.)

As is seen in figure 1, the CIE chromaticity diagram (to be explained in greater detail in section 2.3.3) can be used to define the confusion lines for dichromats because the colors which appear to be the same to a particular type of dichromat all lie on a straight line radiating from a single point (Fry, 1944). This point is different for each type of dichromat. In addition to color confusions, brightness perceptions may also differ from normal in those with color defects. The most drastic change is that reds become very dark for protanopic and protanomalous observers.

One important aspect of the abnormal color perceptions of anomalous trichromats can be measured by the use of an anomaloscope, an instrument in which pure yellow light is matched by a mixture of red and green. The proportion of red to green needed for a match with yellow indicates whether the observer is "red-weak" (protanomalous), "green-weak" (deuteranomalous), or color-normal. Anomalous trichromats require three primaries to match a given color, but use different proportions than would a normal trichromat (Brindley, 1970). Thus, for example, pure yellow is seen at about 578.3 nm for a deuteranomal, 583 for a protanomal, and 576 nm for a color normal observer (Linksz and Waaler, 1968). While the color confusions of anomalous observers are somewhat similar to those of the corresponding class of dichromats, they do not involve the confusion of entire lines of color in the chromaticity diagram, as is found with dichromatic observers. Because of their prevalance, color confusions should be considered in designing a system of safety colors for populations not selected for normal color vision. In fact, because the common screening devices for color-vision defects are very far from fully effective in detecting anomalous trichomats, it is desirable to allow for red-green confusions even for populations thought to be screened for normality. Bailey (1965) suggests that such tests may pass as many as 75 percent of color-anomalous observers, for example.

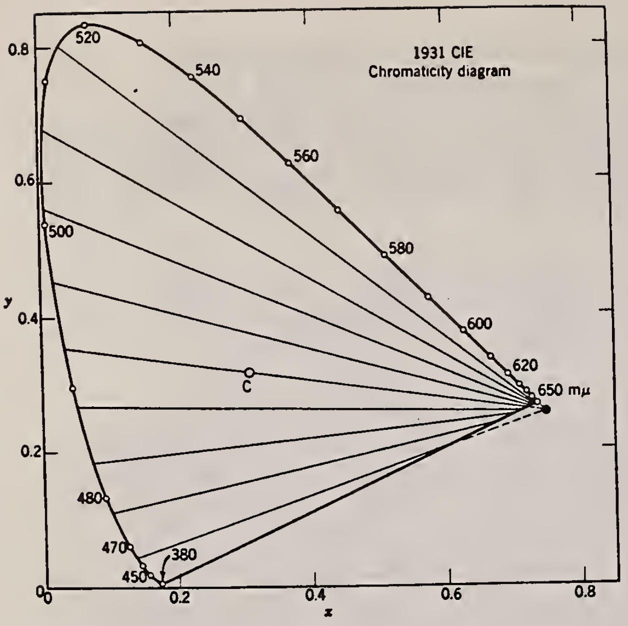


Figure 1a. Protanopic chromaticity confusions shown on the (x,y) chromaticity diagram

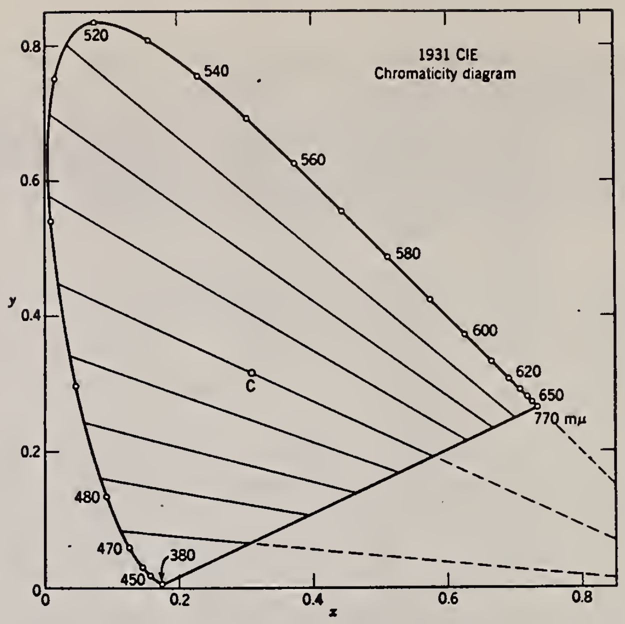


Figure 1b. Deuteranopic chromaticity confusions shown on the (x,y) chromaticity diagram

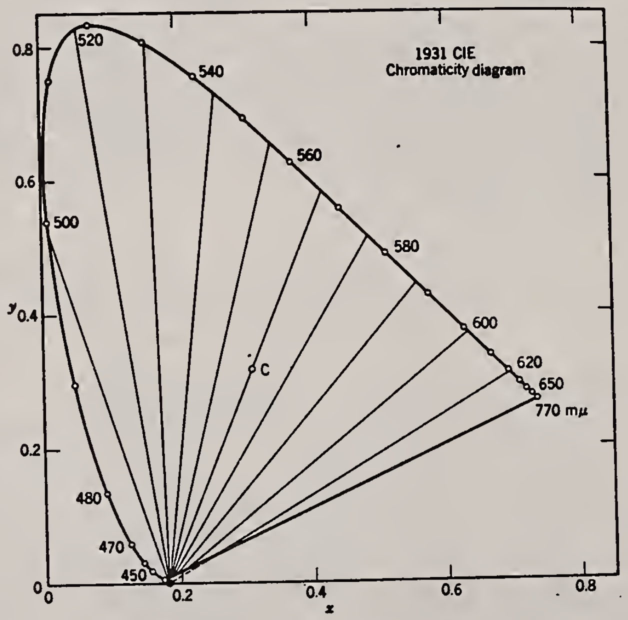


Figure 1c. Tritanopic chromaticity confusions shown on the (x,y) chromaticity diagram

Figure 1. Confusion lines of dichromats
Figures reproduced from Judd and Wyszecki, Color in Business, Science, and Industry, Second Edition, (1963) with permission of John Wiley and Sons, New York.

2.3.2 Visual Adaptation

In addition to the physiological defects in color vision that have already been discussed, there are also normal moment-to-moment variations in visual sensitivity as a result of adaptation to different light sources. Three kinds of adaptation occur--light adaptation, in which the eye's sensitivity decreases rather quickly following a change to a higher level of illumination; dark adaptation, in which the sensitivity increases more slowly following a change to a lower level; and chromatic adaptation, in which the chromatic sensitivity of the eye shifts with a change in the color of the light source. Dark adaptation occurs when an observer goes from a brightly lit area, such as outside, to a dimly lit interior space. Depending on the darkness of the second space, a finite period of time, from 1 to 30 minutes, is required to attain the new higher level of visual sensitivity. During this time, because the scene being viewed is so much dimmer, the person can lose the ability to perceive objects and colors, until the eye adapts to the new luminance level. The reverse process of light adaptation, occurs much more rapidly--on the order of 1 to 2 minutes (Cornsweet, 1970). During this very brief transition, a person can be temporarily blinded, as happens when leaving a darkened theater on a sunlit day.

Chromatic adaptation occurs when a person spends time exposed to a light source of a particular color. When the person moves to an area lit by a different source, chromatic sensitivity will be altered progressively as the eye readapts (Hurvich, 1981). By way of illustration, suppose the initial light source is not pure white, but somewhat bluish. After exposure to this light for some time, the bluish stimulation fatigues the blue receptors of the eye proportionately more than the red or green receptors. Now suppose that the second source is pure white in color. Although it supplies equal stimulation to all three color receptors, it does not appear white to the blue adapted person. Rather, it appears yellow, because the blue receptors are fatigued and respond proportionately less than the red and green receptors. (Yellow is the result of simultaneous red and green receptor stimulation.) This result is temporary, however, because the white light is no longer disproportionately stimulating the blue receptors so that they recover their sensitivity, and the initially yellow-appearing light soon appears white. Thus, the effect of the chromatic adaptation process is to cause simultaneous changes in both sensitivity and color perception with the net result, after adaptation is complete, being some degree of stability in the perceived colors of objects under various light sources.

Marked chromatic adaptation will occur to a narrow band illuminant such as low pressure sodium whose dominant wavelength of 589 nm stimulates the red photoreceptors most strongly, the green receptors somewhat less strongly, and the blue receptors not at all. As a result, color perception is noticeably distorted during the first few minutes of subsequent exposure to a "white" light. There is an initial greenish-blue cast to everything because the blue receptors have remained highly sensitive, while the red receptors have become highly insensitive and the green receptors are in between.

2.3.3 Specification of Color Appearance

For a color to be seen as such, the light source shining on the surface must supply light of the appropriate wavelength. Thus, a "red surface appears red because it selectively absorbs wavelengths other than red, and it reflects more of the long wavelengths than of those in the middle or short wavelength end of the visible spectrum. Sources, surfaces, and media that are not differentially selective in the wavelengths they send, reflect, or transmit to the eye are seen as 'achromatic' rather than colored. They appear black, gray or white" (Schiff, 1980, p. 35). Note, however, that the red object cannot preferentially reflect long wavelengths if no long wavelengths are supplied by the light source. The worst type of light source for general illumination is a monochromatic (one wavelength) source; no object, regardless of its reflectance spectrum, can send any light to the observer's eye other than that one wavelength, since no other wavelength is there to reflect. Consequently, use of a monochromatic light will drastically alter the appearance of a colored object compared with "white" light. To deal with the problem of the way in which a light source can alter the perception of color, the CIE (1974) developed a Color Rendering Index (CRI) for specifying the color rendering properties of a light source. The IES (1981, p. I-8) defines color rendering as "the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under a reference light source." The Color Rendering Index provides a "measure of the degree of color shift objects undergo when illuminated by the light source as compared with the color of the same objects when illuminated by a reference source of comparable color temperature" (IES, 1981, p. I-8). The IES mentions that the CRI does not yet completely account for chromatic adaptation or color constancy, but that it does provide an agreed-upon means of comparing lamps for color rendition.

Specification of exactly what is meant when one gives a name such as "red" to a color even under ordinary daylight is not easily done. Does one mean "red", "magenta", "pink", or "burgundy"? How can one specify "red" so that another person can understand and reproduce the intended color? To address this problem, a number of color specification systems have been developed. Major systems for specifying object colors include the Munsell system, the ISCC-NBS color names, and the CIE Chromaticity diagram. Each will be discussed briefly in turn.

The Munsell color system organizes a set of 1600 color chips into a three-dimensional solid. Hurvich (1981, p. 275) describes it this way: "The individual chips are ordered into a three-dimensional color solid with a vertical black-to-white axis. HUES are arranged in equal angular spacing around the central axis and CHROMA (saturation) is the distance of a chip from the central axis at any given VALUE (lightness) level." Specifications for particular Munsell colors are given by three sets of alphanumeric characters which specify hue, value, and chroma.

The ISCC-NBS system of color names is a coarser subdivision of object-color space than the Munsell system. The ISCC-NBS system is based on the use of simple color names, easily understood without training. The blocks in color

space corresponding to the ISCC-NBS color names are defined in terms of Munsell notation. Kelly and Judd (1976) discussed the idea of a Universal Color Language (UCL) which would include both the ISCC-NBS color naming system and the Munsell notation system. As they summarized it, the Universal Color Language is "a method or language of designating colors in simple, easily understood but accurately defined color designations in definite, correlated levels of accuracy of color designation" (p. A-18). The UCL describes six levels of increasing color specification accuracy. In each level, the complete color solid is divided into specified numbers of color blocks; the boundaries for each block are defined; and each level is related to all other levels. In level one, colors are specified in terms of 13 common color names. These 13 blocks are further subdivided into 29 blocks for level 2. Level 3 constitutes the ISCC-NBS method of designating colors, using a full set of 267 color names. Level 4 is divided into about 1,500 blocks, corresponding to the Munsell system. In level 5 the Munsell system is subdivided further by visual interpolation into even finer detail. Finally, in level 6, color is measured instrumentally and specified numerically by the CIE chromaticity coordinate system (to be discussed below). Thus, the UCL provides a way of systematically defining the appearance of colors. These specifications apply only to colors seen under average daylight or CIE source C.

Another system for specifying the color of an object or light is given in its most familiar form by the CIE chromaticity diagram. This system is based on the principle that three fixed colored lights (or "primaries") can be mixed to match any color (by means of a colorimeter or other instrument). The amounts of the three primaries needed to match the color are called tristimulus values. To avoid variations in matches between observers, the CIE specified a "Standard Observer", based upon the average values of a substantial number of observers (Wyszecki and Stiles, 1967). The color matching data of the CIE 1931 Standard Observer are considered representative of the normal human eye. The system is defined by three functions of wavelength, $\bar{x}$, $\bar{y}$, and $\bar{z}$ which represent the tristimulus values of the single wavelengths of the spectrum. (The primaries of the CIE system were chosen in such a way that these spectral tristimulus values are all-positive functions. Other choices of primaries can result in negative values.) Hurvich (1981, p.284) states: "To specify any illuminated object or surface colorimetrically we only require the object's or surface's spectral reflectance or transmittance and the spectral energy distribution (in relative terms) of the light source illuminating it. If the products of these two distribution curves at each wavelength are then multiplied by each of the standard observer spectral tristimulus values at each wavelength and the resultant values for all wavelenths added separately, we obtain the three numbers needed to specify the color. These three summed values are called the X, Y, and Z tristimulus values." The chromaticity coordinates x, y, and z are fractional equivalents of X, Y, and Z; i.e., $X = X/(X+Y+Z)$, etc. Because the CIE chromaticity coordinates are fractions which sum to unity, if two coordinate values are known, the third can be derived arithmetically. This principle has been used to develop the CIE chromaticity diagram, which is a two-dimensional diagram upon which the x and y coordinates are plotted (see figure 2). This diagram can be used to plot the chromaticity of any object, thus enabling its color to be specified without reference to a set of color chips or standard colors.

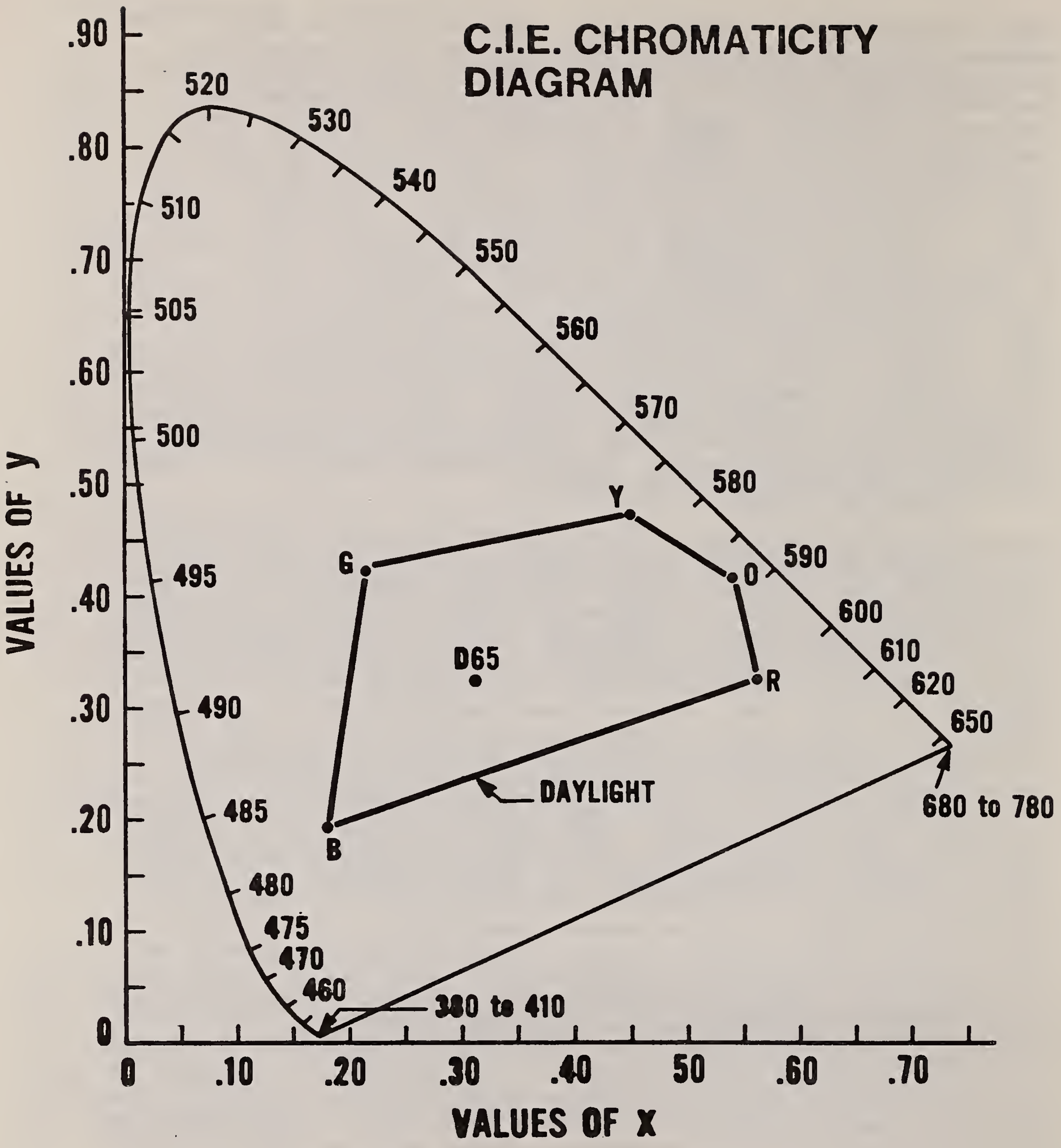


Figure 2. CIE chromaticity diagram containing the ANSI standard safety colors illuminated by daylight

In addition to the diagram itself, figure 2 plots the chromaticity values of the five basic ANSI standard safety colors for daylight illumination. Since the spectral reflectance of the object, and the relative energy distribution of the illuminant are the physical measures from which these coordinates are calculated, the accuracy of the coordinates is limited only by the accuracy of the physical measurements. Three-decimal-place accuracy of x and y is currently routine, and under special circumstances, the fourth place can be meaningful.

As an illustration of the three systems of color specifications discussed above, an example can be taken from the ANSI Z53.1-1979 Standard for Safety Colors (ANSI, 1979). This standard specifies Safety Red by the Munsell notation 7.5R 4.0/14. The 7.5R portion indicates the specific red hue; 4.0 the Munsell value (slightly below the medium lightness of value 5); and 14 the Munsell chroma, a quite high saturation. The standard also gives the equivalent CIE notation, which, to three figures, is $x = 0.596$, $y = 0.327$, and $Y(\%) = 12.00$. The Y value, in the CIE system, is used to indicate the percentage luminous reflectance of the color sample. Finally, the descriptive ISCC-NBS color name is given by the standard as vivid red.

2.3.4 Color Coding Research

Color has been used extensively to code information (often when speed of communication is desirable). Christ (1975) analyzed data from 42 studies to assess the effect of color coding on visual performance. He found that when subjects were asked to identify two aspects of a visual display, such as color and shape, identification of color was more rapid and more accurate. Color was particularly superior as the number of stimuli increased, although it remained inferior to alphanumeric coding (perhaps the most familiar coding dimension). Christ (1975, p. 559-560) commented that "The most clear-cut finding is that if the color of a target is unique for that target, and if that color is known in advance, color aids both identification and searching." Only alphanumeric characters emerge as a superior coding dimension to color. Use of irrelevant colors, however, may interfere with the accuracy and speed of identifying or locating target attributes other than color. For the purposes of workplace signage, however, Christ's review underscores the ability of color to attract attention and encode relevant safety information in a rapid, accurate fashion. Color is particularly effective in a redundant cueing situation where the audience is knowledgeable about the color code--as is the case with signs in workplaces. Other individual studies have reinforced the finding that color is a particularly effective coding device. Thus, Saenz and Riche (1974), Shontz, Trumm, and Williams (1971), and Smith and Thomas (1964), found that color coding reduced search time and increased accuracy. This advantage is most clear-cut if the number of colors in the code does not exceed 8 to 10 (Cahill and Carter, 1976). Another study, by Easterby and Hakiel (1977), did not find clear evidence of the superiority of color coding. This study, which assessed symbol recognition, found that image content, perhaps comparable in information capacity to the alphanumeric characters discussed earlier, was more important than color coding in determining sign recognition. Yet, their subjects reported strong stereotypes for the use of color for fire, poison, and caustic hazard-warning symbols. Bresnahan and Bryk (1975) reported that industrial subjects associated red and yellow with a rated degree of

hazard warning, thus suggesting that sign color can aid in communicating both the presence and level of hazard.

In summary, the preceding review of some color coding research underlines the importance of color coding in communicating information both rapidly and accurately. Unlike shape or size, color appears to be more effective, particularly if the code is limited to about 8 to 10 colors. Only alphanumeric characters (and perhaps pictorial symbols) are more effective coding dimensions than color--and this may be due to widespread familiarity with the characters. The use of color as a known, redundant cue appears to be highly effective, however, thus suggesting that the use of color-coded word/symbol signs is one of the best means of communicating safety information at least in the United States.

2.4 SIGN PERCEPTION

2.4.1 Background Research and Practice

Written signs are commonly used in industrial settings to alert workers to the presence of hazards and to provide safety information and instructions. They are particularly important in alerting the new worker who is unfamiliar with the job and industrial setting. These people are at higher risk during the initial months on the job (National Safety Council, 1979)

Recommendations about the effective use of signs assume that such messages are legible and visible in industrial settings. A number of factors may alter the visibility of such signs, however. These include low levels of illumination, poor contrast, poor color rendering, poor positioning, inadequate size, and poor durability. The effectiveness of signs can also be reduced by excessive visual clutter in the immediate neighborhood of the signs, including the presence of too many other signs. Even a single sign can be over-cluttered, with the inclusion of too many words or symbols.

2.4.2 Observed Sign Use

In a document prepared for NIOSH, Lerner and Collins (1980) reported site visits to six industrial plants to observe safety symbol, sign, and color use. Although they dealt mainly with sign use, they also documented different industrial uses of safety colors that are relevant to the present report. The six industrial sites studied represented a diverse range of industries, and included: the manufacture and assembly of truck engines, ceramic glass, aircraft, ships, as well as chemical and oil refining. These authors found that safety signs related more to potentially serious hazards such as explosion, fire, or the need for protective gear, with somewhat less reliance upon signs for frequently occurring but less serious hazards (such as slips, trips, and falls). With the exception of one site, the common practice was to use word signs, often quite lengthy signs. Of particular interest to the present report, was the widespread use of color coding to delineate areas for special protective gear or particular hazard. For example, yellow lines were commonly used to indicate a generally hazardous area; green to indicate the need to wear protective equipment or the presence of a safe walkway; orange for explosives; red for

fire-related equipment or high hazard area. In contrast to signs, here the color was used as the entire message with the workers having presumably learned the meaning of the color code before entering the job site. Lerner and Collins found that the use of yellow as a hazard warning was widespread and was used to indicate the extent of hazardous areas; moving parts and equipment; overhead hazards (such as cranes); and occasionally to indicate areas where personal protective equipment was mandatory (a message sometimes coded with green, as well). These authors commented that, in some worksites, because of the extensive use of color coding, signs were infrequently used. In addition, color coding could be more spatially precise, indicating the exact area where certain behaviors were expected.

Another question that Lerner and Collins addressed was the ways in which signs were presented.

> They state (1980, p. 24) that: "In other words, where are they typically located, how are they illuminated, where are they located with respect to the hazards they represent, and what is the background against which they are presented? Although such details are expected to vary, there were highly idiosyncratic practices and extreme variability in sign presentation among the sites visited. Even the same message, Eye Protection Required, was presented in many different ways: signs were placed on stands in the aisles, or mounted on walls (sometimes well above eye level and out of the usual visual field), or above entrance ways, or on fixtures and equipment. Often, signs were presented in clusters, rather than singly. Lighting varied from signs poorly placed in shadow, to ones placed in bright illumination. Warnings were placed at entrances, sometimes located around the workspace, and other times mounted on or near the hazard. [Warning is used generically here to refer to the entire class of hazard warning signs, including those for danger and caution, as well as warning.] Sometimes warning signs were difficult to see due to clutter, poor maintenance, or blending into the background color. (In some cases the predominant workplace color was yellow to yellow-green, making yellow warning signs obscure). As a result, no 'typical' or 'representative' contexts were identified. What is a familiar context in one setting appears unusual in another plant or even in another section of the same plant due to differences, in hazards, layout, and sign usage."

Although this study was limited to six workplaces, it did identify a number of different industrial practices for colors and signs, and reinforced the need to study the appearance of safety colors under different illuminants.

2.4.3 Symbol Sign Research

Symbolic signs are also used to provide information, because, when their meaning is known, they can be recognized more rapidly and accurately than comparable word signs (Janda and Volk, 1934; Walker, Nicolay, and Stearns, 1965). Because symbol signs are effective in communicating information without

the use of a specific written language, they are used where language or literacy barriers may exist. (They can be effective only when the target audience understands the intended meaning, however.) Both word and symbol signs are used as a common means of warning personnel and reinforcing safe actions. Laner and Sell (1960) determined, for example, that safety posters using both pictures and words were effective in increasing safe behavior, even over a period of several weeks.

While the bulk of symbol research concentrated upon symbols for highway and automotive applications, a number of studies addressed the issue of safety symbols. Easterby, for example, conducted a series of studies on symbols for consumer products and determined that for symbols for fire, poison and caustic hazards, people preferred descriptive symbols to prohibitory symbols. They also tended to prefer graphically more complex symbols to simpler, more abstract symbols (Easterby and Hakiel, 1977). The image content of the symbol was, not surprisingly, found to be the factor which most determined the recognizability of a symbol, far more than color or overall shape coding.

Lerner and Collins (1980) and Collins and Pierman (1979) conducted several assessments of fire-safety symbols which uncovered severe problems with selected graphic renditions of the "exit" and "no exit" messages. At least one "no exit" symbol was found which communicated the message of "exit" or "safe haven" more sucessfully than it did "no exit". These authors pointed out that situations in which symbols communicate a message opposite to the intended one are potentially very dangerous.

Collins, Lerner, and Pierman (1980) assessed the meaningfulness of 2 to 3 sets of proposed images for 33 hazard warning and safety information messages, with 222 employees from industrial plants in 3 separate geographical locations. They found that understandability varied widely for different symbols, with symbols for laser, radiation, general warning and biohazard being poorly understood. Yet, symbols for personal protective gear, first aid, prohibition, and fire emergency were generally well understood. The understandability of the symbol appeared to be related, at least, in part to its inclusion of a person with the depicted hazard, action, or equipment, and in part to the pictorial nature of many of the symbols.

This work was extended by Collins (1983) to an evaluation of symbols for 40 messages for mining applications. These two studies identified a set of symbols which successfully convey hazard warning and safety information. Problems were seen for the very abstract symbols such as radiation and biohazard, as well as for the more representational flammable hazard symbol. Recommended symbols based upon the results of both studies are presented in figure 3.

In the course of the project on mine-safety symbols, Collins also had about 220 miners rate the perceived hazardousness of a set of surround shapes (octagon, diamond, triangle, inverted triangle, circle, and square) for different interior images (poison, explosion, entanglement, general warning, and no image). The results indicated that the diamond was ranked as most hazardous consistently, with the octagon a very close second. The two triangles were ranked next, with the circle and square consistently ranked as least hazardous. Because the

Figure 3. Symbols suggested for safety messages

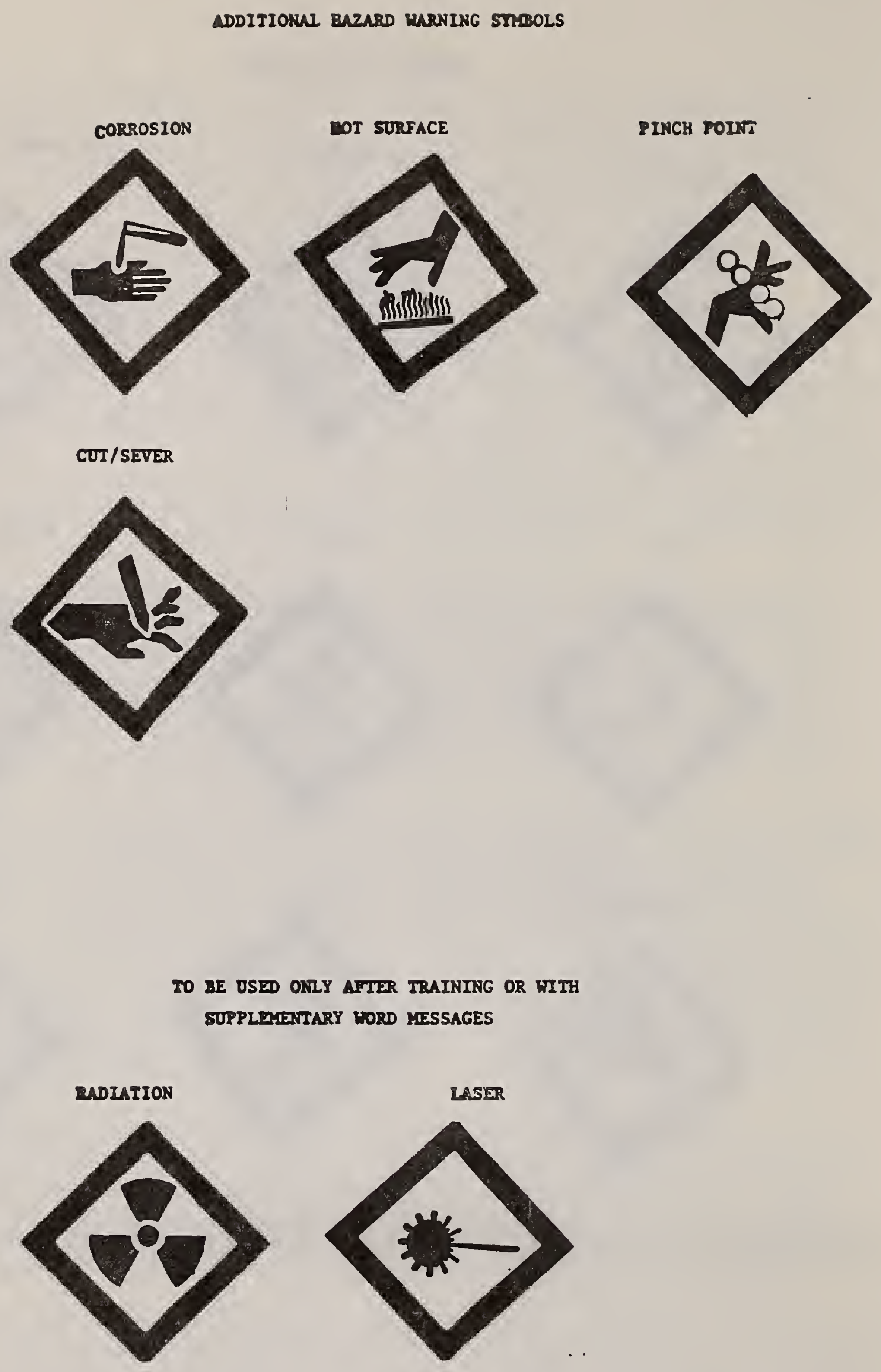


Figure 3. Symbols suggested for safety messages

PERSONAL PROTECTIVE
GEAR (MANDATORY ACTION)

EYE PROTECTION

HARD HAT

EAR PROTECTION

SAFETY GLOVES

SAFETY SHOES

SAFETY EQUIPMENT

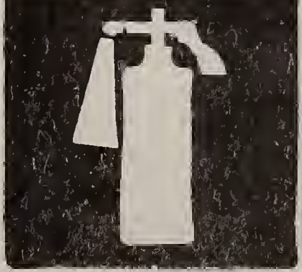
FIRST AID

EYEWASH

SAFETY SHOWER

FIRE EMERGENCY EQUIPMENT

FIRE EXTINGUISHER



FIRE HOSE AND REEL

Figure 3. Symbols suggested for safety messages

Figure 3. Symbols suggested for safety messages

diamond is used by the Department of Transportation (1978) to indicate warning, because it allows a larger interior image than the ISO-recommended triangle, and because it was generally ranked as most hazardous, Collins (1983) suggests that it be given further consideration as the surround shape for hazard warning.

The effectiveness of combined word and symbol signs remains to be examined. Current sign practice typically follows the ANSI Z35 format (to the extent that any format is used). This format uses a signal word such as Danger, Caution, or Notice, with a short word message which describes the hazard or recommended action. The communicative value of adding symbols to these word signs remains to be assessed. Furthermore, the overall legibility of such combined signs also needs to be determined.

3. LABORATORY STUDY OF COLOR APPEARANCE UNDER DIFFERENT LIGHTS

3.1 BACKGROUND

The preceding sections have indicated that the use of color and signs to indicate the presence of hazards and to convey safety information in workplaces is both common and prescribed by regulation. The use of high-efficiency, poor color-rendering light sources can markedly affect the legibility of a word or symbol message, when it reduces the contrast between the message and its immediate background. Moreover, it can drastically alter the perceived color of such a sign, thus nullifying the attempt to convey safety information through color coding. Current color rendering indices do not adequately specify the extent to which such a source would alter the perception of safety colors. A low index value is a signal that possible color distortions should be looked for, but this value provides little information about how colors will be perceived and identified.

As a result NBS undertook a laboratory study to assess the extent to which different types of light sources affect the perception of a number of colors, including safety colors. This study was intended to define the kind and extent of shifts in color appearance for a number of common workplace illuminants, including tungsten, metal halide, fluorescent, high pressure sodium, and low pressure sodium. These light sources vary widely in color rendering index, with none having a spectral distribution substantially equivalent to CIE Standard Illuminant C, for which the current ANSI Z53.1 (1979) safety colors were specified, or D65, the current CIE daylight standard. Consequently, it was hypothesized that some of these sources might result in a marked decrease in the ability to identify safety colors correctly. As a result, several series of colors of different composition, including ordinary, fluorescent, retroreflective, and retroreflective fluorescent, were studied under the light sources mentioned above. (The ordinary color series included the standard ANSI Z53.1 safety colors.)

It was hoped that the pilot laboratory study would assess the identifiability of the different types of color samples under the different light sources, and that a small set of colors could be determined which were maximally identifiable under all five sources. Such a set of colors could then be evaluated more extensively under both laboratory and field conditions to determine their suitability for general workplace use.

3.2 METHOD

3.2.1 Subjects

Seven employees of the National Bureau of Standards, three females and four males, participated in the present study. The mean age was 37.3 with a range of 21 to 55. All subjects had normal (20/20) or corrected-to-normal visual acuity. They also had normal color vision, as verified by the A.O. H-R-R Pseudo-Isochromatic Plates.

3.2.2 Apparatus

All experimental sessions were conducted in the Illumination Color Laboratory which contained an 8 ft 5 in. by 6 ft 5 in. illumination chamber, with an 8 ft ceiling and removable black walls. Illumination was provided by one of five different energy-efficient or high-color-rendering lighting systems. These systems included low pressure sodium (LPS), high pressure sodium (HPS), metal halide (MH), fluorescent (FL), and incandescent tungsten (T). Table 3 presents illuminance data for each light source. Figure 4 presents spectral power distribution data, including chromaticity and correlated color temperature, for each of the five sources. Schematic design details are given in figure 5, with additional detail presented in appendix A.

The color samples used in this experiment consisted of four series of 5 in. by 7 in. color samples mounted in frames. The four series consisted of samples of the ANSI safety colors (designated series 100); an additional series of ordinary colors, intermediate between the ANSI colors (designated series 200); retroreflective colors, some of which were also fluorescent (series 300); and a fluorescent (non-retroreflective) series (series 400). Two samples for a number of colors from series 100 and 200 were used as controls, to determine if color names varied within an individual sample. The total number of color samples from all four series was 73, of which 45 were distinct colors. A listing of each series, sample number, and color name is given in table 4.

The 100 series of colors were the central or standard colors as specified by ANSI Z53.1 (1979). The 200 series consisted of a set of colors approximately halfway between the standard ANSI (chromatic) colors, plus a set of experimental red colors formed by various mixtures of different red pigments. The 300 series consisted of some samples of conventional retroreflective color material, such as is used on highway signs, plus some samples of a new type of material that is both fluorescent and retroreflective. The 400 series of colors consisted of regular fluorescent paints of the sort used in "black-light" displays.

3.2.3 Procedure

Experimental sessions began with a 15, 30, 45, or 60 minute adaptation period to one of the following light sources: low pressure sodium with 1 (low) or 3 (high) lamps lit; high pressure sodium; tungsten; metal halide; or fluorescent. The shortest adapting time, 15 minutes, should have been long enough to ensure full light adaptation (typically believed to occur in about 1 to 2 minutes; Cornsweet, 1970). The adapting illuminance levels are given in table 3. The lowest illuminance level, 15 fc, is well into the photopic visual range, so that color discrimination should not have been adversely affected. To avoid influencing color judgments, the black-walled chamber was devoid of colored objects. During the adaptation period in the illumination chamber, subjects performed various visual tasks such as reading, writing, etc. Upon completion of adaptation, the subject was seated 3 feet from the eye level viewing area. A black cloth was draped around the subject to ensure a color-free visual environment.

Table 3. Average Horizontal and Vertical Foot-Candles for Each Light Source Measured for a Horizontal and a Vertical Surface

Light Source	Horizontal	Vertical
Low Pressure Sodium-Low Level	59.75	48.04
Low Pressure Sodium-High Level	143.04	105.91
High Pressure Sodium	52.63	43.58
Metal Halide	13.73	15.91
Tungsten	46.50	32.57
Fluorescent	35.54	32.15

Table 4. Experimental Color Samples - Series 100-400

ANSI Sample Series - 100

Series	Color Name
100/105*	ANSI Purple
110/115	ANSI Blue
120/125	ANSI Green
130/135	ANSI Yellow
140/145	ANSI Orange
150/155	ANSI Red
160/165	ANSI Brown
170/175	ANSI Black
180/185	ANSI Grey
190/195	ANSI White

Regular Sample Series - 200

Series	Color Name/Composition
201/202	10 PB
203/204	10 BG
205/206	5 GY
207/208	10 YR
209/210	2.5 YR
211/212	7.5 YR
213	QR-T
214	QR-OP
215	QR-2
216	QR-4
217	QR-6
218	Safety Red
219	Bon Maroon-1
220	Bon Maroon-2
221	Bon Maroon-3
222	Bon Maroon-4
223	Bon Maroon
224	Bon M & TI 02-1
225	Bon M & TI 02-2
226	Bon M & TI 02-3

Retroreflective-Fluorescent Sample Series - 300

Series	Color Name
300	R. Blue**
301	R. Blue-Green**
302	R.F. Green
303	R.F. Yellow-Green
304	R. Yellow**
305	R.F. Orange
306	R. Orange-Brown**
307	R.F. Red-Orange
308	R. Red**
309	R.F. Purplish-Red
310	R. White**

Fluorescent Sample Series - 400

Series	Color Name/Composition
400	S. Yellow/S. Green
401/402	Saturn Yellow Toned W/Green
403	S. Yellow
404	Orange (Mix A)
405	D/G Blaze Orange
406/407	D/G Fire Orange
408	S. Red
409	D/G Rocket Red
410	Rocket Red-Quinon Red 1:1
411	Rocket Red-Safety Red 2:1-1
412	Rocket Red-Safety Red 1:2-2
413	Rocket Red-Safety Red 1:1-3
414	Rocket Red-Bon Maroon 1:1
415	Rocket Red-Bon Maroon 2:1

* Two color samples separated by a slash were identical. This duplication includes all samples in series 100, and samples in sets 201-212, 401/402, and 406/407.

** Retroreflective only, not fluorescent colors.

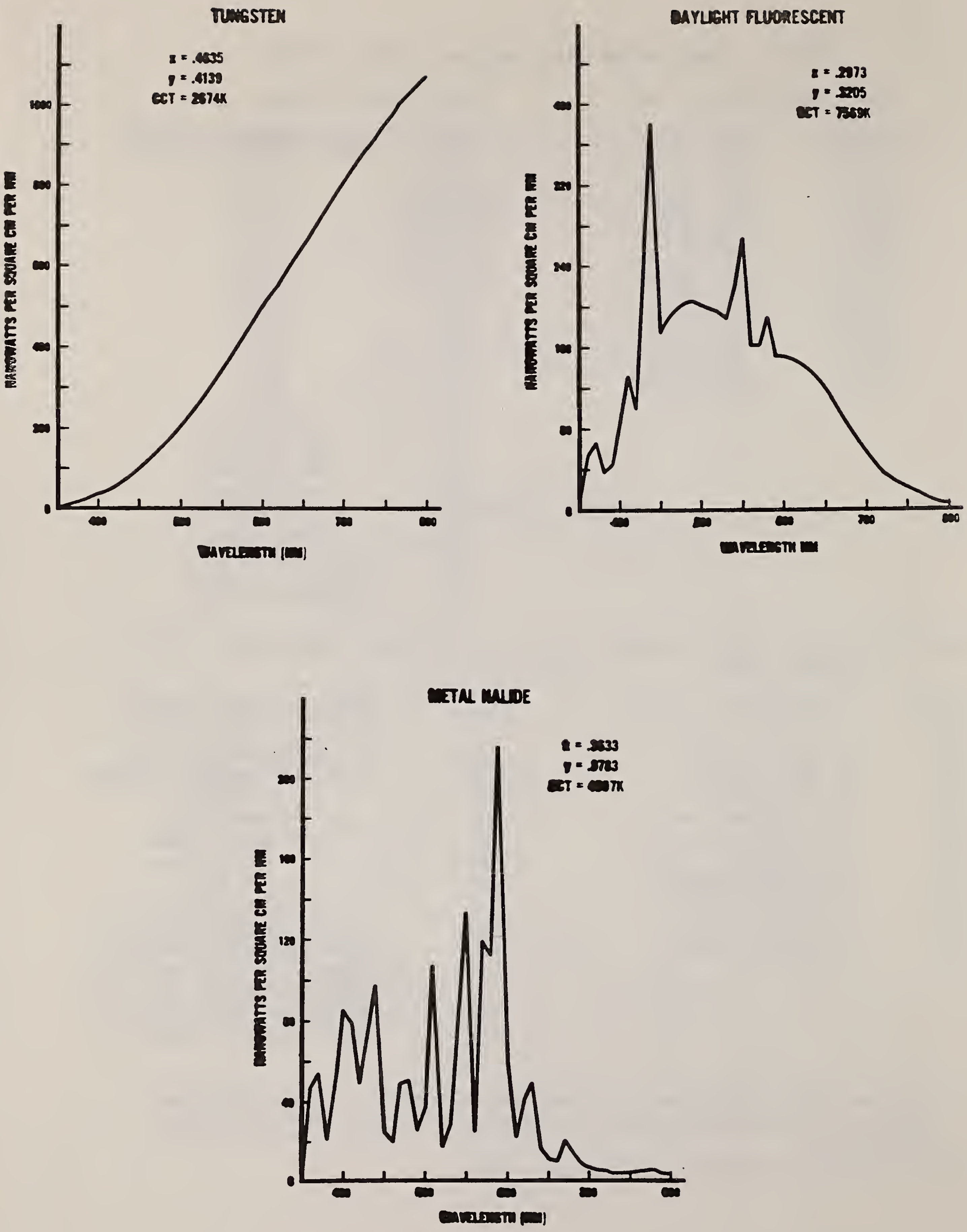
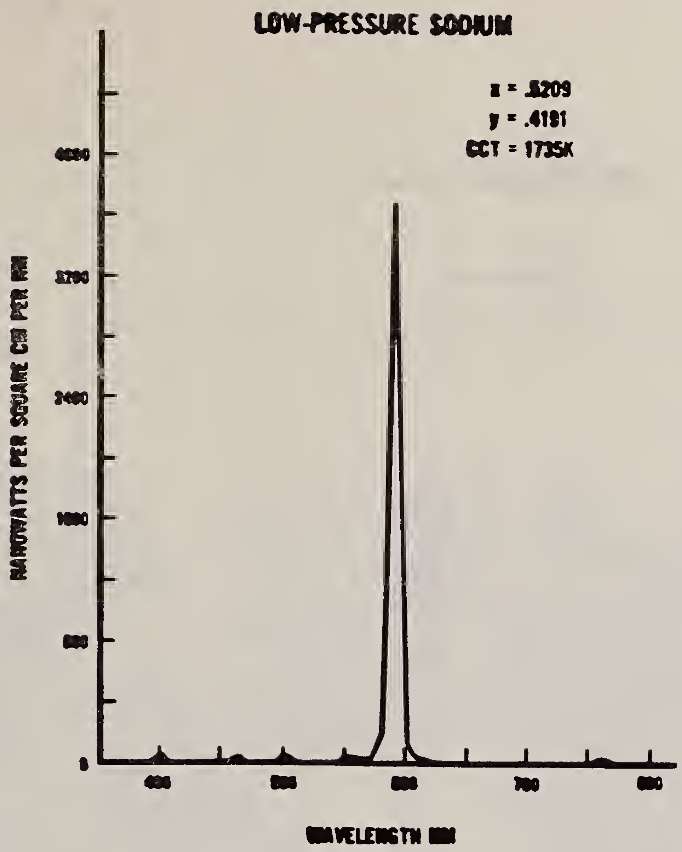


Figure 4. Spectral Power Distributions of Experimental Light Sources



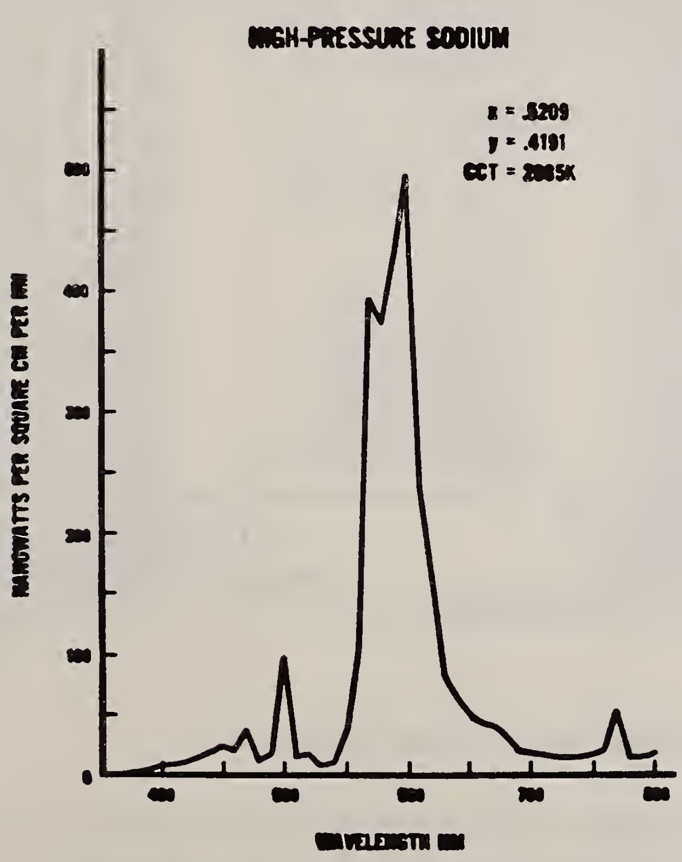


Figure 4. Spectral Power Distributions of Experimental Light Sources

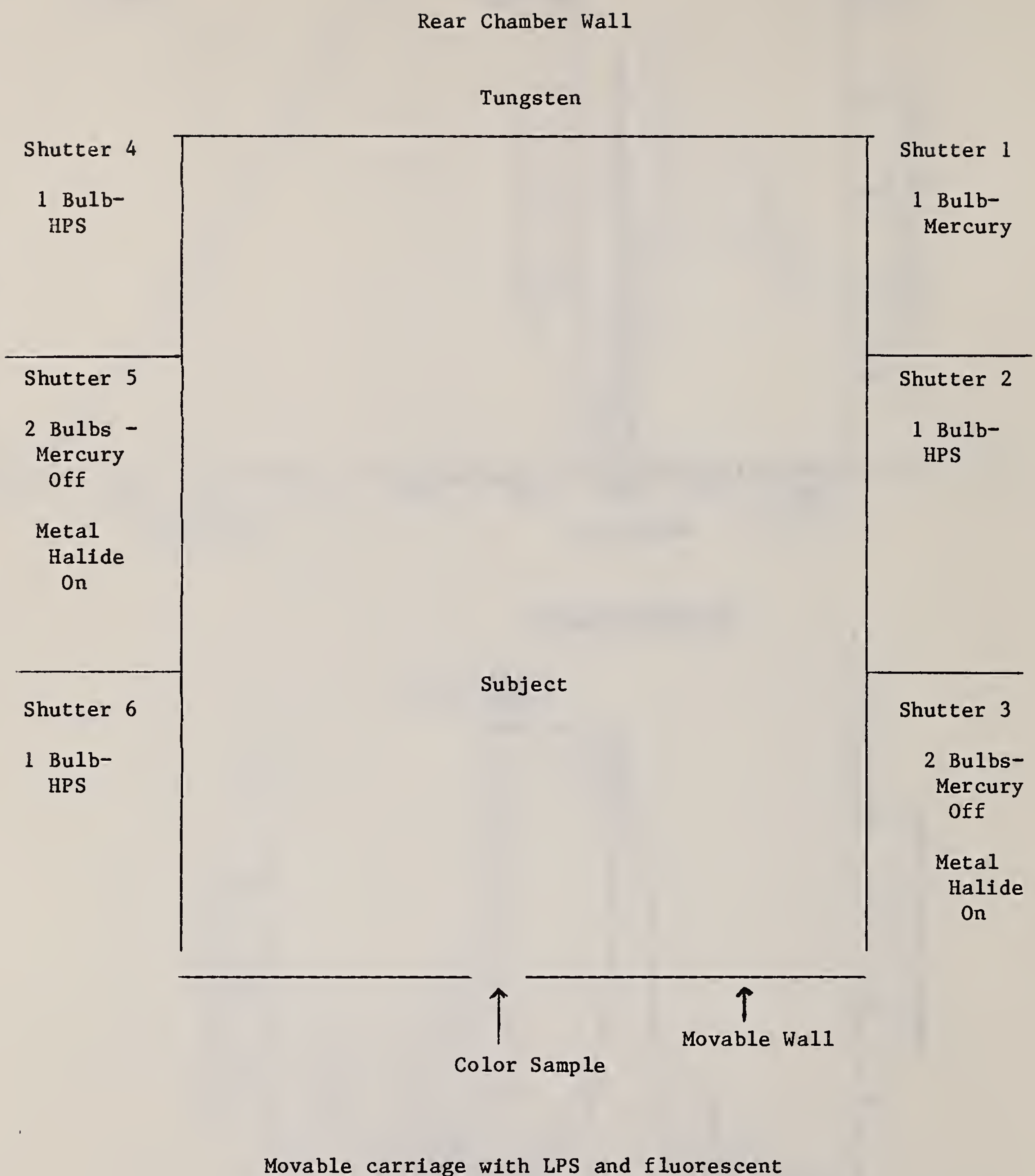


Figure 5a. Design details of illumination color laboratory

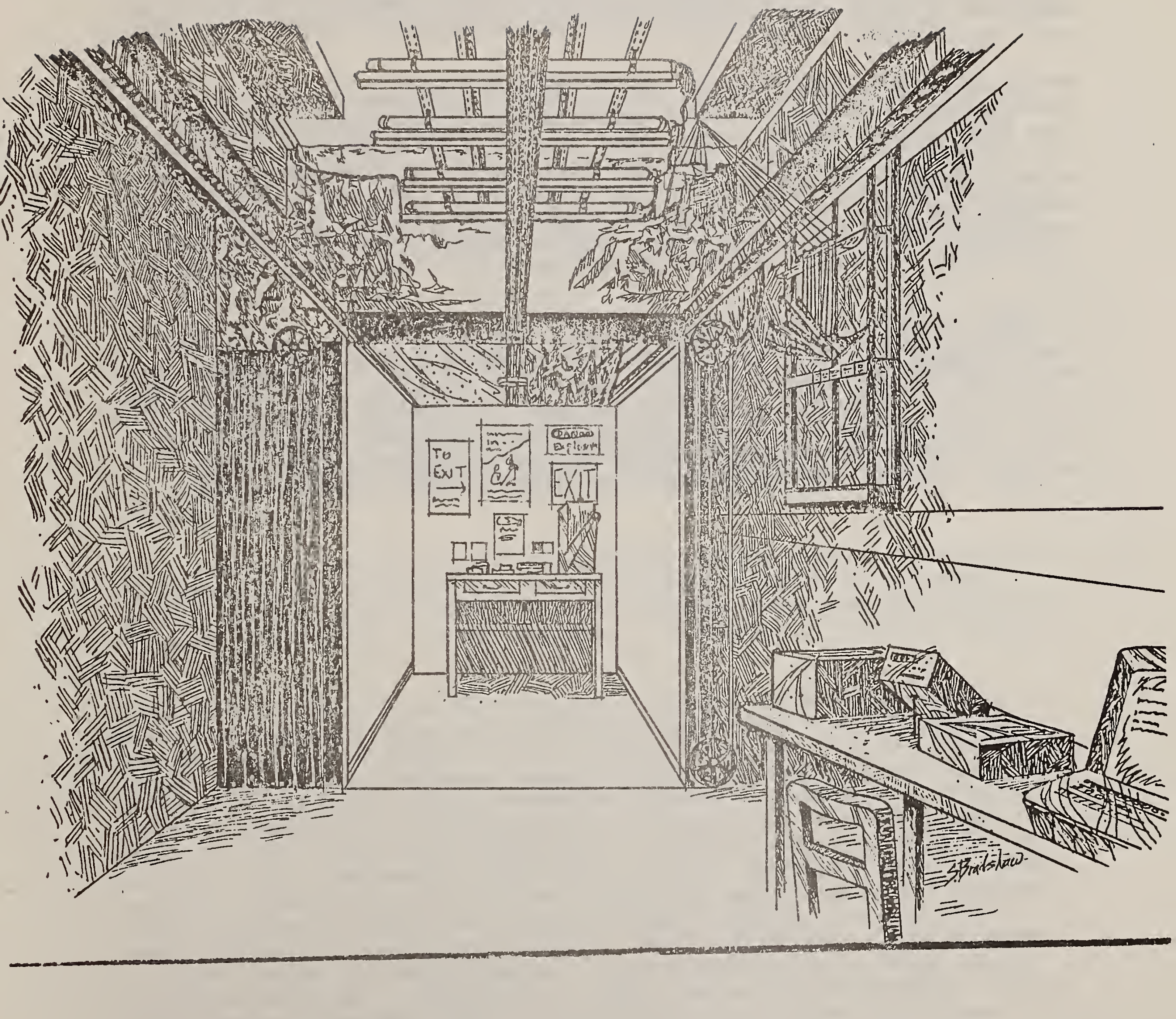


Figure 5b. Sketch of illumination color laboratory

Once the experiment began, the subject (always run individually) named the sample's dominant color and its secondary color, if any. Each subject also indicated the sample's lightness (light, medium, dark) on a simple three-category scale, as well as its saturation (strong, medium, weak). Thus, a typical response to a sample that appeared to be orange with some red tint to it might have been "orange/red, medium, medium", or a pure blue sample might have been termed "blue, dark, strong". These responses were recorded by an experimenter. (Lightness and saturation judgments were not included in the final data analysis, because subjects could not make consistent ratings for these two measures. More exhaustive training in the three color variables, as specified by the Munsell system, is necessary if consistent judgments of lightness and saturation are desired.)

During each experimental session, one of the five light sources provided the illumination. Each session lasted approximately 30 minutes plus adaptation time (typically 30 minutes also). About 50 color samples randomly drawn from each of the four color series were presented during each experimental session. Although samples were available for all safety colors, the experimental presentations concentrated on red and orange samples, from the 100, 300, and 400 series, because of the need to find a "red" perceived as red--the color used to symbolize the highest degree of danger--under all light sources, including LPS.

In all, a total of 116 experimental sessions were held, with a total of 5760 sample presentations. (Fewer sessions were conducted with the 200 series because of the experimental nature of this set of samples.) The greatest number of sessions per sample (51) was conducted under low pressure sodium, since this light source results in the greatest color distortion. Twenty four sessions per sample were conducted under high pressure sodium; fifteen under tungsten; thirteen under metal halide, and thirteen under fluorescent light.

4. RESULTS

4.1 FREQUENCY DISTRIBUTIONS

The color naming responses were tabulated and analyzed by a series of computerized data acquisition and manipulation programs. For the purpose of the present report, color-name frequencies for each color sample were totaled (collapsed) across subjects, adaptation periods, and illumination levels, since preliminary inspection of the data revealed no differences due to these variables.

Tables 5 to 8 present a frequency distribution of the number of times that a particular sample was given one of twelve color names under each of the five light sources. Decimal fractions of the total are also given, following the frequency counts, in each column. These color names included the five basic safety colors--red, orange, yellow, green, and blue; the auxiliary colors--purple, brown, grey, white, and black--as well as the combination categories of red/orange, and orange/red. To create these tables, several categories of color names were combined together. These combinations disregarded the use of any secondary color name. Thus, blue/green was included with blue, rather than with green. The only exceptions to this rule were orange/red and red/orange which were categorized separately due to the special interest in "red" as a safety color name. In addition to being identified separately, the red/orange responses were included in the total "Red" count, and the orange/red responses were included in the total "Orange" count. (Frequency data for orange/red and red/orange only are given in parentheses.) In those few instances, where subjects gave color names which were not standard safety color names, these were included with the most appropriate color name. Such combinations included olive with green, gold with yellow, pink with red, and tan with brown.

Table 5 presents data for the 100 color series; table 6 presents data for the 200 series; table 7 presents data for the 300 series; and table 8 presents data for the 400 series. Table 9 presents the color names that were given as secondary responses in a "blend" response, as a function of the five different light sources.

Examination of tables 5 to 8 (frequencies) indicates the extent to which a particular sample was given one or more color names under the different light sources. For the 100 series (table 5), purple, blue, and green (samples 100 to 125) were generally correctly identifed under all light sources, except LPS. Under this source, these samples were typically identified as brown or gray. An exception to this generality is that green was frequently termed blue under HPS. (Note that samples ending in five were duplicates in the 100 series). The yellow sample (130/135) was correctly identified under all light sources. Orange (140/145) was termed orange only under tungsten and fluorescent lights, both orange and yellow under metal halide and HPS, and only yellow under LPS. The red color sample (150/155) caused considerable confusion under all light sources including tungsten. It was termed yellow or brown under LPS, orange under HPS, and more often orange than red for metal halide. Under fluorescent and tungsten lights, it was called red more often than orange.

Table 5. Color Frequency Charts*

100 Series

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
PURPLE 100													
LPS			2-0.06	5-0.15					16-0.47		10-0.29	1-0.03	34
HPS		12-0.92						1-0.08					13
MH		8-1.00											8
FL		8-1.00											8
T		11-1.00											11
PURPLE 105													
LPS				5-0.19					11-0.42		10-0.38		26
HPS	1-0.11	8-0.88											9
MH		6-1.00											6
FL		8-1.00											8
T		9-1.00											9
BLUE 110													
LPS		2-0.06							12-0.39	3-0.10	14-0.45		31
HPS	12-1.00												12
MH	7-1.00												7
FL	11-1.00												11
T	8-1.00												8
BLUE 115													
LPS	1-0.03	2-0.07							10-0.34	1-0.03	15-0.52		29
HPS	16-1.00												16
MH	8-1.00												8
FL	7-1.00												7
T	11-1.00												11
GREEN 120													
LPS									10-0.32	2-0.06	19-0.61		31
HPS	8-0.50		8-0.50										16
MH	2-0.22		7-0.78										9
FL	1-0.09		10-0.91										11
T	1-0.09		10-0.91										11
GREEN 125													
LPS									12-0.38		20-0.62		32
HPS	7-0.64		4-0.36										11
MH			5-1.00										5
FL	1-0.12		7-0.88										8
T			11-1.00										11

* The first number refers to the frequency; the second to the percentage of total responses for each individual sample.

Table 5. (Continued)

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
YELLOW 130													
LPS				33-1.00									33
HPS				15-1.00									15
MH			1-0.14	6-0.86									7
FL				6-1.00									6
T				7-1.00									7
YELLOW 135													
LPS				26-1.00									26
HPS				14-1.00									14
MH				10-1.00									10
FL			1-0.10	9-0.90									10
T				10-1.00									10
ORANGE 140													
LPS				39-1.00									39
HPS				14-0.78	3-0.17				1-0.06				18
MH				4-0.40	6-0.60								10
FL				1-0.14	6-0.86	(1-0.14)							7
T				1-0.09	10-0.91								11
ORANGE 145													
LPS				40-1.00									40
HPS				8-0.53	7-0.47								15
MH				6-0.75	2-0.25								8
FL				2-0.29	5-0.71								7
T					8-1.00								8
RED 150													
LPS			2-0.06	16-0.44					11-0.31		7-0.19		36
HPS					13-0.87			2-0.13					15
MH				1-0.08	6-0.50	(1-0.08)		4-0.33	1-0.08				12
FL							(1-0.14)	7-1.00					7
T					1-0.09		(3-0.27)	10-0.91					11
RED 155													
LPS			1-0.03	13-0.42	1-0.03				10-0.32		6-0.19		31
HPS					10-0.83		(1-0.08)	2-0.17					12
MH				1-0.17	3-0.50	(1-0.17)	(1-0.17)	2-0.33					6
FL					2-0.16	(2-0.16)	(2-0.16)	10-0.83					12
T				1-0.08	4-0.33	(2-0.17)	(3-0.25)	7-0.58					12

Table 5. (Continued)

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
BROWN 160													
LPS			1-0.04	3-0.12				1-0.04	13-0.52		7-0.28		25
HPS				4-0.25					12-0.75				16
MH									4-1.00				4
FL									8-1.00				8
T									7-1.00				7
BROWN 165													
LPS			4-0.14	5-0.17					11-0.38		9-0.31		29
HPS			2-0.20	3-0.30					5-0.50				10
MH									8-1.00				8
FL					1-0.13				7-0.87				8
T									11-1.00				11
BLACK 170													
LPS	1-0.04	4-0.16							4-0.16	14-0.56	2-0.08		25
HPS	1-0.08									11-0.92			12
MH										10-1.00			10
FL										8-1.00			8
T										8-1.00			8
BLACK 175													
LPS	4-0.14	4-0.14							7-0.24	10-0.34	4-0.14		29
HPS									2-0.11	15-0.83	1-0.06		18
MH										8-0.89	1-0.11		9
FL										9-1.00			9
T										13-1.00			13
GRAY 180													
LPS			1-0.03	16-0.55					4-0.14		7-0.24	1-0.03	29
HPS											13-1.00		13
MH			1-0.17								5-0.83		6
FL											5-0.83	1-0.17	6
T		1-0.13									7-0.87		8
GRAY 185													
LPS				13-0.59					4-0.18		4-0.18	1-0.05	22
HPS			1-0.07								11-0.73	3-0.20	15
MH	1-0.11		1-0.11								6-0.66	1-0.11	9
FL	1-0.20										3-0.60	1-0.20	5
T											8-1.00		8

Table 5. (Continued)

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
WHITE 190													
LPS				17-1.00									17
HPS												15-1.00	15
MH								1-14.3				6-85.7	7
FL												5-1.00	5
T												4-1.00	4
WHITE 195													
LPS				21-1.00									21
HPS												11-1.00	11
MH												6-1.00	6
FL												3-1.00	3
T												6-1.00	6

Table 6. Color Frequency Charts

200 Series

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
PURPLE/BLUE 201													
LPS			1-0.07	1-0.07					7-0.47		6-0.40		15
HPS		9-0.90						1-0.10					10
MH	1-0.14	6-0.86											7
FL	2-0.33	4-0.66											6
T		3-1.00											3
PURPLE/BLUE 202													
LPS			1-0.06						11-0.65		5-0.29		17
HPS		9-1.00											9
MH		3-1.00											3
FL	2-0.50	2-0.50											4
T		3-1.00											3
BLUE/GREEN 203													
LPS									5-0.31	1-0.06	9-0.56	1-0.06	16
HPS	10-1.00												10
MH	7-1.00												7
FL	7-1.00												7
T	5-1.00												5
BLUE/GREEN 204													
LPS									4-0.27	1-0.07	10-0.67		15
HPS	8-1.00												8
MH	4-1.00												4
FL	9-1.00												9
T	5-1.00												5
GREEN/YELLOW 205													
LPS				12-0.86								2-0.14	14
HPS			14-0.93	1-0.07									15
MH			9-1.00										9
FL			4-1.00										4
T			2-1.00										2
GREEN/YELLOW 206													
LPS				14-0.88							2-0.12		16
HPS			8-0.73	3-0.27									11
MH			5-1.00										5
FL			5-1.00										5
T			3-1.00										3
YELLOW/ORANGE 207													
LPS				15-1.00									15
HPS				13-1.00									13
MH				5-1.00									5
FL				5-0.83	1-0.17								6
T				5-1.00									5

Table 6. (Continued)

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
YELLOW/ORANGE -208													
LPS				25-1.00									25
HPS				15-0.94	1-0.06								16
MH				7-0.88	1-0.12								8
FL				4-1.00									4
T				5-0.83	1-0.17								6
ORANGE/RED -209													
LPS				19-0.95								1-0.05	20
HPS			1-0.10	2-0.20	7-0.70								10
MH					6-1.00								6
FL					8-1.00								8
T					5-1.00	(1-0.20)							5
ORANGE/RED -210													
LPS				18-1.00									18
HPS				5-0.45	5-0.45				1-0.09				11
MH				1-0.14	6-0.86	(1-0.14)							7
FL					6-1.00								6
T					5-1.00								5
RED/PURPLE -211													
LPS				24-0.92					2-0.08				26
HPS								8-1.00					8
MH								1-1.00					1
FL		6-1.00											6
T		1-0.17						5-0.83					6
RED/PURPLE -212													
LPS				26-1.00									26
HPS								11-1.00					11
MH		1-0.33						1-0.33				1-0.33	3
FL		6-0.75										2-0.25	8
T		2-0.25						6-0.75					8
ORANGE/RED -213													
LPS				16-0.64					7-0.28		2-0.08		25
HPS					4-0.80	(2-0.40)	(1-0.20)	1-0.20					5
MH								3-1.00					3
FL								2-1.00					2
T					1-0.14		(1-0.14)	6-0.86					7
ORANGE/RED -214													
LPS				7-0.33					9-0.43		5-0.24		21
HPS					13-0.87	(4-0.27)	(2-0.23)	2-0.13					15
MH								5-1.00					5
FL					1-0.17	(1-0.17)		5-0.83					6
T								5-1.00					5

Table 6. (Continued)

	BLUE	PURPLE	(Olive) GREEN	(Gold) YELLOW	ORANGE	O/RED	RED/O	(Pink) RED	(Tan) BROWN	BLACK	GRAY	WHITE	N
ORANGE/RED 215													
LPS			3-0.10	17-0.59					4-0.14		4-0.14	1-0.3	29
HPS					7-1.00	(1-0.14)							7
MH					2-0.50	(2-0.50)	(1-0.25)	2-0.50					4
FL				1-0.25				3-0.75					4
T					1-0.25	(1-0.25)		3-0.75					4
ORANGE/RED 216													
LPS				6-0.26					11-0.48		5-0.22	1-0.04	23
HPS					11-0.92	(2-0.17)	(1-0.08)	1-0.08					12
MH					1-0.33	(1-0.33)	(1-0.33)	2-0.67					3
FL							(1-0.17)	6-1.00					6
T					1-0.10	(1-0.10)	(2-0.20)	9-0.90					10
ORANGE/RED 217													
LPS				12-0.48					8-0.32		5-0.20		25
HPS					8-0.80		(2-0.20)	2-0.20					10
MH							(2-0.50)	4-1.00					4
FL								5-1.00					5
T					3-0.30	(2-0.20)	(2-0.20)	7-0.70					10
ORANGE/RED 218													
LPS			1-0.03	20-0.69					4-0.14		4-0.14		29
HPS					7-0.87	(2-0.25)		1-0.13					8
MH					3-0.60			2-0.40					5
FL								5-1.00					5
T					2-0.22		(4-0.44)	7-0.78					9
MAROON 219													
LPS			1-0.04	3-0.12	1-0.04				12-0.48		8-0.32		25
HPS					4-0.40		(3-0.30)	6-0.60					10
MH								7-1.00					7
FL								4-1.00					4
T								9-1.00					9
MAROON 220													
LPS			1-0.03						21-0.66		10-.31		32
HPS							(5-0.45)	11-1.00					11
MH								8-1.00					8
FL								7-1.00					7
T								8-1.00					8
MAROON 221													
LPS									19-0.76	2-0.08	4-0.17		25
HPS							(1-0.09)	11-1.00					11
MH		1-0.25						3-0.75					4
FL								4-1.00					4
T								5-1.00					5

Table 6. (Continued)

	BLUE	PURPLE	(Olive) GREEN	(Gold) YELLOW	ORANGE	O/RED	RED/O	(Pink) RED	(Tan) BROWN	BLACK	GRAY	WHITE	N
MAROON 222													
LPS		1-0.05						2-0.11	14-0.74	2-0.11			19
HPS								9-1.00					9
MH		1-0.12						7-0.88					8
FL								3-1.00					3
T								6-1.00					6
BON MAROON 223													
LPS	5-0.17								7-0.24	17-0.59			29
HPS								8-1.00					8
MH								7-1.00					7
FL								5-1.00					5
T								7-1.00					7
BON MAROON 224													
LPS	6-0.23	1-0.04							5-0.19	14-0.54			26
HPS								11-1.00					11
MH		1-0.14						6-0.86					7
FL								6-1.00					6
T								6-1.00					6
BON MAROON 225													
LPS	1-0.05	5-0.24						1-0.05	11-0.52		3-0.14		21
HPS		3-0.43						4-0.57					7
MH		4-1.00											4
FL		1-0.50						1-0.50					2
T								8-1.00					8
BON MAROON 226													
LPS		1-0.05						2-0.09	13-0.59	1-0.05	5-0.23		22
HPS	1-0.17	1-0.17						4-0.67					6
MH		5-1.00											5
FL		3-1.00											3
T	1-0.20							4-0.80					5

300 Series

	BLUE	PURPLE	(Olive) GREEN	(Gold) YELLOW	ORANGE	O/RED	RED/O	(Pink) RED	(Tan) BROWN	BLACK	GRAY	WHITE	N
BLUE 300													
LPS	36-0.80									9-0.20			45
HPS	24-1.00												24
MH	12-1.00												12
FL	13-1.00												13
T	15-1.00												15
BLUE/GREEN 301													
LPS	34-0.69									13-0.26	2-0.04		49
HPS	12-0.50		12-0.50										24
MH			13-1.00										13
FL			13-1.00										13
T	1-0.07		14-0.93										15
GREEN 302													
LPS				3-0.07					16-0.36	4-0.09	20-0.45	1-0.02	44
HPS			23-1.00										23
MH			13-1.00										13
FL			13-1.00										13
T			14-0.93		1-0.07								15
YELLOW/GREEN 303													
LPS				42-0.98								1-0.02	43
HPS			12-0.63	7-0.37									19
MH			11-0.85	2-0.15									13
FL			9-0.69	4-0.31									13
T			9-0.60	6-0.40									15
YELLOW 304													
LPS				47-1.00									47
HPS			1-0.04	22-0.92					1-0.04				24
MH				11-0.85	2-0.15								13
FL				13-1.00									13
T				13-0.87	2-0.15								15
ORANGE 305													
LPS				7-0.17	29-0.71			5-0.12					41
HPS					23-1.00								23
MH					13-1.00								13
FL					13-1.00								13
T					12-1.00								12
ORANGE/BROWN 306													
LPS				47-0.98								1-0.02	48
HPS				7-0.37	9-0.47				3-0.16				19
MH				4-0.33	8-0.67								12
FL				1-0.09	9-0.82				1-0.09				11
T				1-0.07	14-0.93								15

Table 7. (Continued)

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
RED/ORANGE 307													
LPS					34-0.72	(7-0.15)	(7-0.15)	13-0.28					47
HPS					19-0.83	(1-0.4)	(4-0.17)	4-0.17					23
MH					9-0.69		(4-0.31)	4-0.31					13
FL					12-0.92	(4-0.31)	(1-0.08)	1-0.08					13
T					13-0.93	(3-0.21)		1-0.07					14
RED 308													
LPS			2-0.04	13-0.28					20-0.42		12-0.26		47
HPS					18-0.82	(1-0.04)	(1-0.04)	4-0.18					22
MH				4-0.31	6-0.46	(4-0.31)	(1-0.05)	3-0.13					13
FL					1-0.08		(1-0.08)	12-0.92					13
T					3-0.23	(1-0.08)	(2-0.15)	10-0.77					13
RED 309													
LPS				3-0.06	37-0.80	(2-0.04)		6-0.13					46
HPS					7-0.30	(1-0.04)	(2-0.09)	16-0.70					23
MH							(2-0.15)	13-1.00					13
FL					1-0.08			11-0.85				1-0.08	13
T							(1-0.07)	14-1.00					14
WHITE 310													
LPS				42-0.91					1-0.02		3-0.07		46
HPS									1-0.04		4-0.17	18-0.78	23
MH		1-0.08									6-0.50	5-0.42	12
FL											6-0.50	6-0.50	12
T											7-0.47	8-0.53	15

Table 8. Color Frequency Charts

400 Series

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
YELLOW/GREEN 400													
LPS				48-1.00									48
HPS			5-0.24	16-0.76									21
MH			11-0.85	2-0.15									13
FL			6-0.50	6-0.50									12
T			9-0.60	6-0.40									15
YELLOW/GREEN 401													
LPS				29-0.64				1-0.02	2-0.04		9-0.20	4-0.09	45
HPS			24-1.00										24
MH			13-1.00										13
FL			12-0.92	1-0.08									15
T			15-1.00										15
YELLOW/GREEN 402													
LPS			1-0.02	28-0.58					9-0.19		8-0.17	2-0.04	48
HPS			24-1.00										24
MH	1-0.08		11-0.92										12
FL			12-0.92	1-0.08									13
T			15-1.00										15
YELLOW 403													
LPS				50-1.00									50
HPS			3-0.12	21-0.88									24
MH			5-0.38	8-0.62									13
FL			4-0.31	8-0.61	1-0.08								13
T			5-0.33	10-0.67									15
ORANGE 404													
LPS				45-0.98								1-0.02	46
HPS				21-1.00									21
MH				13-1.00									13
FL				12-0.92	1-0.08								13
T				13-0.87									15
ORANGE 405													
LPS				1-0.02	39-0.80	(9-0.18)	(2-0.04)	9-0.18					49
HPS					20-0.83	(5-0.21)	(3-0.12)	4-0.17					24
MH				2-0.15	10-0.77			1-0.08					13
FL					12-0.92	(3-0.23)	(1-0.08)	1-0.08					13
T					12-0.80	(2-0.13)	(3-0.20)	3-0.20					15

Table 8. (Continued)

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GREY	WHITE	N
ORANGE 406													
LPS					8-0.17	(5-0.11)	(16-0.35)	38-0.83					46
HPS					12-0.50	(4-0.17)	(6-0.25)	12-0.50					24
MH					5-0.42	(3-0.25)	(2-0.17)	7-0.58					12
FL					9-0.69	(5-0.38)	(2-0.15)	4-0.31					13
T					10-0.67	(4-0.27)	(3-0.20)	5-0.33					15
ORANGE 407													
LPS					11-0.23	(8-0.17)	(11-0.23)	37-0.77					48
HPS					9-0.39	(4-0.17)	(8-0.35)	14-0.61					23
MH					5-0.42	(2-0.17)	(3-0.25)	7-0.58					12
FL					7-0.54	(4-0.31)	(4-0.31)	6-0.46					13
T					9-0.60	(6-0.04)	(4-0.27)	6-0.40					15
RED 408													
LPS				1-0.02	8-0.17	(6-0.12)	6-0.12	39-0.81					48
HPS					5-0.23	(2-0.09)	7-0.32	17-0.77					22
MH					1-0.08		2-0.15	12-0.92					13
FL					2-0.15	(1-0.08)	4-0.31	11-0.85					13
T					4-0.27	(1-0.07)	4-0.27	11-0.73					15
RED 409													
LPS					6-0.12	(1-0.02)	(12-0.24)	44-0.88					50
HPS					6-0.25	(3-0.12)	(5-0.21)	18-0.75					24
MH				2-0.15	2-0.15	(2-0.15)	(1-0.08)	9-0.69					13
FL					4-0.31	(2-0.15)	(4-0.31)	9-0.69					13
T					5-0.33	(3-0.20)	(3-0.20)	10-0.67					15
RED 410													
LPS					14-0.29	(8-0.16)	(13-0.26)	35-0.71					49
HPS					10-0.43	(3-0.13)	(7-0.30)	13-0.57					23
MH					1-0.08		(1-0.08)	12-0.92					13
FL					3-0.23	(1-0.08)	(1-0.08)	10-0.77					13
T					6-0.40	(3-0.20)	(2-0.13)	9-0.60					15
RED 411													
LPS					29-0.60	(7-0.14)	(11-0.23)	19-0.40					48
HPS					12-0.52	(4-0.17)	(7-0.30)	11-0.48					23
MH					1-0.08		(3-0.23)	12-0.92					13
FL					2-0.17	(1-0.08)	(2-0.17)	10-0.83					12
T					5-0.38	(1-0.08)	(3-0.23)	8-0.62					13
RED 412													
LPS					42-0.84	(2-0.04)	(1-0.02)	8-0.16					50
HPS					21-0.88	(8-0.33)	(1-0.04)	3-0.12					24
MH					5-0.38	(3-0.23)	(1-0.08)	8-0.62					13
FL					2-0.15	(1-0.08)	(1-0.08)	11-0.85					13
T					6-0.40	(2-0.13)	(5-0.33)	9-0.60					15

Table 8. (Continued)

	BLUE	PURPLE	GREEN	YELLOW	ORANGE	O/RED	RED/O	RED	BROWN	BLACK	GRAY	WHITE	N
RED													
413													
LPS					41-0.82	(4-0.08)	(2-0.04)	9-0.18					50
HPS					14-0.61	(3-0.13)	(4-0.17)	9-0.39					23
MH					3-0.23	(3-0.23)	(3-0.23)	10-0.77					13
FL					1-0.08		(1-0.08)	10-0.83				1-0.08	13
T					6-0.43	(3-0.21)	(2-0.14)	8-0.57					14
414													
LPS					5-0.11	(1-0.02)	(6-0.13)	41-0.87	1-0.02				47
HPS					4-0.17	(2-0.09)	(1-0.4)	19-0.83					23
MH								13-1.00					13
FL								13-1.00					13
T					2-0.14	(1-0.07)	(1-0.07)	13-0.87					15
415													
LPS					10-0.21	(1-0.02)	(5-0.10)	35-0.73	3-0.06				48
HPS							(1-0.05)	22-1.00					22
MH								13-1.00					13
FL								13-1.00					13
T							(1-0.07)	15-1.00					15

Table 9. Tabulation of Colors Included as Second Color in a Color Blend Response

LPS

Primary	Secondary
Blue	Black
Purple	Gray; red
Green	Yellow; brown; gray
Yellow	Gray; white; green; orange; brown; tan
Gold	Brown; yellow
Orange	Red; brown; pink; yellow; gray
Red	Orange; brown; pink; black; gray; purple
Brown	Gray; yellow; red; black; green; purple; gold
Black	Blue; red; purple
White	Yellow
Gray	Black; white; brown; purple
Pink	Brown; orange; red; yellow; white; magenta
Tan	Yellow; orange
Olive	Yellow

HPS

Primary	Secondary
Blue	Green; red
Purple	Blue
Green	Blue; yellow; brown; tan; gray
Yellow	Green; orange; pink; brown; tan; white
Gold	Brown
Orange	Yellow; pink; brown; tan
Red	Blue; purple; pink; magenta; brown; white
Brown	Green; yellow; orange; red; black
Black	Blue
White	Purple; brown; gray
gray	Violet; purple
Tan	----
Pink	Orange; red; magenta; purple

Metal Halide

Primary	Secondary
Purple	Red; blue; magenta; violet
Blue	Green; white
Green	Yellow; Blue
Yellow	Green; orange; brown
Orange	Brown; pink; red

Table 9. (Continued)

Metal Halide (Continued)

Primary	Secondary
Pink	Purple; red
Red	Purple; blue; pink; magenta; brown; orange
Brown	Yellow; orange; red
Black	----
Grey	Violet
White	Purple; violet; red

Fluorescent

Primary	Secondary
Purple	Blue; violet; pink; red; magenta
Blue	Purple; violet; green; red
Green	Blue; yellow
Yellow	Green; orange; brown; white
Orange	Yellow; pink; brown
Pink	Orange; red
Red	Purple; pink; magenta; brown; white
Brown	Orange
Gray	Blue; violet
White	Purple; blue; red; black
Black	Blue

Tungsten

Primary	Secondary
Blue	Green
Purple	Blue; red; pink
Green	Blue; yellow
Yellow	Green; orange
Orange	Yellow; pink; red
Red	White; blue; purple; pink; brown; orange
Pink	Orange; purple
Brown	Orange; red
Black	Blue (once)
White	Gray

It should be noted that the ANSI Safety Red color is, in fact, not a pure red, as seen under the daylight illuminant for which the ANSI colors were standardized. Rather, this red was deliberately moved slightly toward the orange to assist people with common color defects in distinguishing it from black. Thus, orange as a secondary response, or even as an occasional primary response, under good color-rendering sources is understandable.

Brown (160/165) was accurately identified under all sources except LPS where confusions with gray arose, and under HPS where some confusions with yellow occurred. Black and gray (170/175; 180/185) were generally correctly identified except under LPS where black was termed purple or brown as well as black, and gray was termed yellow. White (190/195) was also termed yellow under LPS, but white under all other sources.

For the 100 series of color samples, the only color correctly identified under all light sources was yellow (130/135). Major confusions arose for safety red (150/155) under all lights, except fluorescent, with both orange and yellow commonly occurring as confusions. The most dramatic--albeit anticipated--pattern of distortion was the shift of the majority of the safety colors to yellow, brown, or gray under LPS, thus indicating an almost total loss of information about the ANSI standard safety colors for this source. This result is to be expected because of the essentially monochromatic spectrum of LPS light, which consists almost entirely of a narrow band around a wavelength of 589 nm, in the yellow-orange region of the visible spectrum.

The data in Table 6, the 200 series, must be regarded as somewhat tentative, due to the generally small number of times each sample was presented under the different sources (particularly tungsten, fluorescent, and metal halide). In addition, part of this set of samples was deliberately designed to be intermediate between the ANSI safety colors, and part to include a variety of different red pigments. Nevertheless, a few general conclusions can be drawn. The green-yellow (205/206) was identified as green more frequently, than Safety Green (120/125), with no blue confusions, under all light sources, except LPS, where it was termed yellow. Yellow-orange (207/208) was not as successful as Safety Yellow, with many confusions with orange for most sources. Another yellow-red sample (209/210) elicited numerous orange responses for all sources except LPS and HPS where a large number of yellow responses arose. Samples 211/212 (red-purple) elicited red, yellow, and purple responses depending upon the source. The remaining samples, 213-226, which consisted of different mixtures of red pigments varying in hue from orangish-red through bluish-red, elicited a variety of yellow, orange or purple responses. Samples 213-218 were generally termed yellow under LPS, orange under HPS and red or orange under the remaining sources. Of the series 219-226, sample 223 was correctly identified under all sources except LPS where it was termed black, brown, or blue. Samples 224 and 225 were also almost as successful. No red in the 200 series was identified as red under LPS, however, although some of these reds were superior (with a higher frequency of correct identifications) to the Safety Red (150/155). Again, however, the reader must be cautioned that a very small number of sample presentations was made.

Table 7 which contains data for the 300 series (retroreflective and retroreflective-fluorescent) indicates that sample 300 is termed blue 80 percent of the time under LPS and blue all the time under all other sources. Sample 300 is thus the sample most consistently identified as blue for all sources, of the samples studied. (Series 400 contained no blue samples.) Sample 302, green, is also quite sucessful, except for LPS where it was termed brown or gray. The other green samples (205/206; 120/125) were usually termed yellow under LPS, thus confusing a hazard warning color with a safety information color. This is a potentially more serious confusion than one with brown which has no hazard connotation.

Sample 305 is one of the most successful orange colors studied, being recognized as such 70 percent of the time under LPS, and all the time under all other light sources. Thus, the 300 series contains samples that had a high percentage of correct identification as blue, green, or orange under all light sources. None of the nominally red samples (307-309), however, were particularly sucessful, with marked confusions occuring between orange and red. In addition, the retroreflective white (310) apparently had too low a reflectance, since it elicited many confusions with gray, except under LPS where it was seen as yellow.

Consideration of the 400 series (fluorescent colors) given in table 8 indicates that samples 401 and 402 were generally identified as green except under LPS, where they were termed yellow, again raising the possiblity of dangerous misinterpretations. Sample 404 was identified as yellow under all sources closely matching the performance of ANSI Safety Yellow (130/135). The greater (combined) absolute frequencies for the latter make those results slightly more convincing, however. In addition, Safety Yellow is an ordinary color, which can generally be expected to be cheaper, and less subject to fading than a fluorescent color.

In the 400 series, samples 405-413 were generally termed as orange or red under all sources with few confusions with other colors such as brown or yellow. Samples 414 and 415, however, had relatively few confusions with orange or orange red, even under LPS, and thus appeared to be the samples most uniquely identifed as red of the four series of samples tested, with 414 the best of all. It should be noted that to excite fluorescence in a pigment, the incident light must contain wavelengths shorter than the re-emitted (fluorescent) light. Thus, since LPS consists almost entirely of a narrow band near the yellow-orange wavelength of 589 nm, it would be expected that only fluorescent orange and red could be excited under LPS. The results for the 400 series confirm that expectation.

Because of the importance of the color red in signalling danger or stop, greater attention was paid to samples which were named as red in the present study. Figures 6 to 10 present the redness percentages for all color samples under each of the five light sources. These figures indicate the fraction of times the primary color of a sample was identified as red under a given light source. Samples not appearing at all in any of these figures were never identified as red under the specified light source. Figures 11 to 15 present similar data

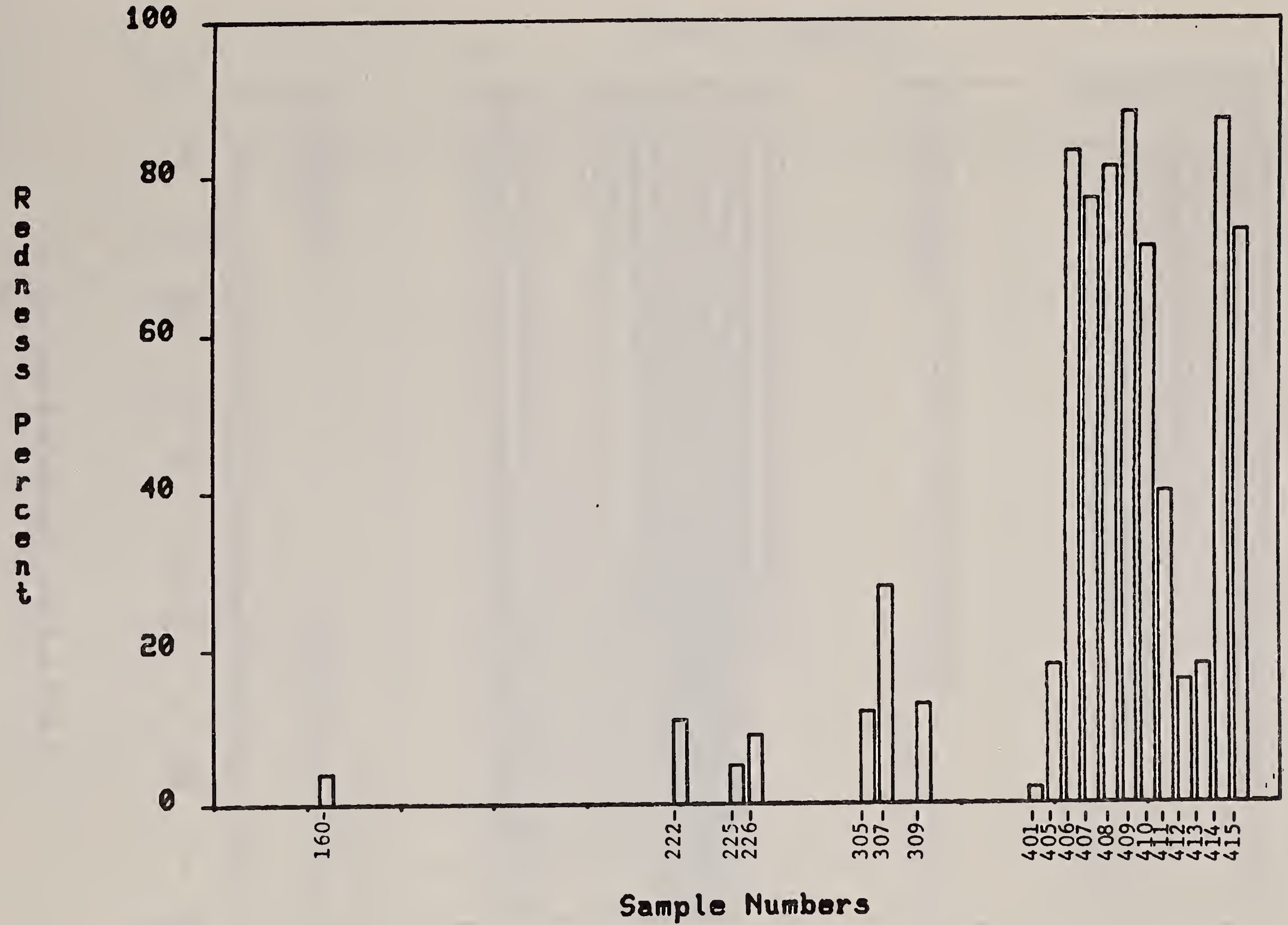


Figure 6. Percentage of trials in which designated color samples were identified as red under LPS

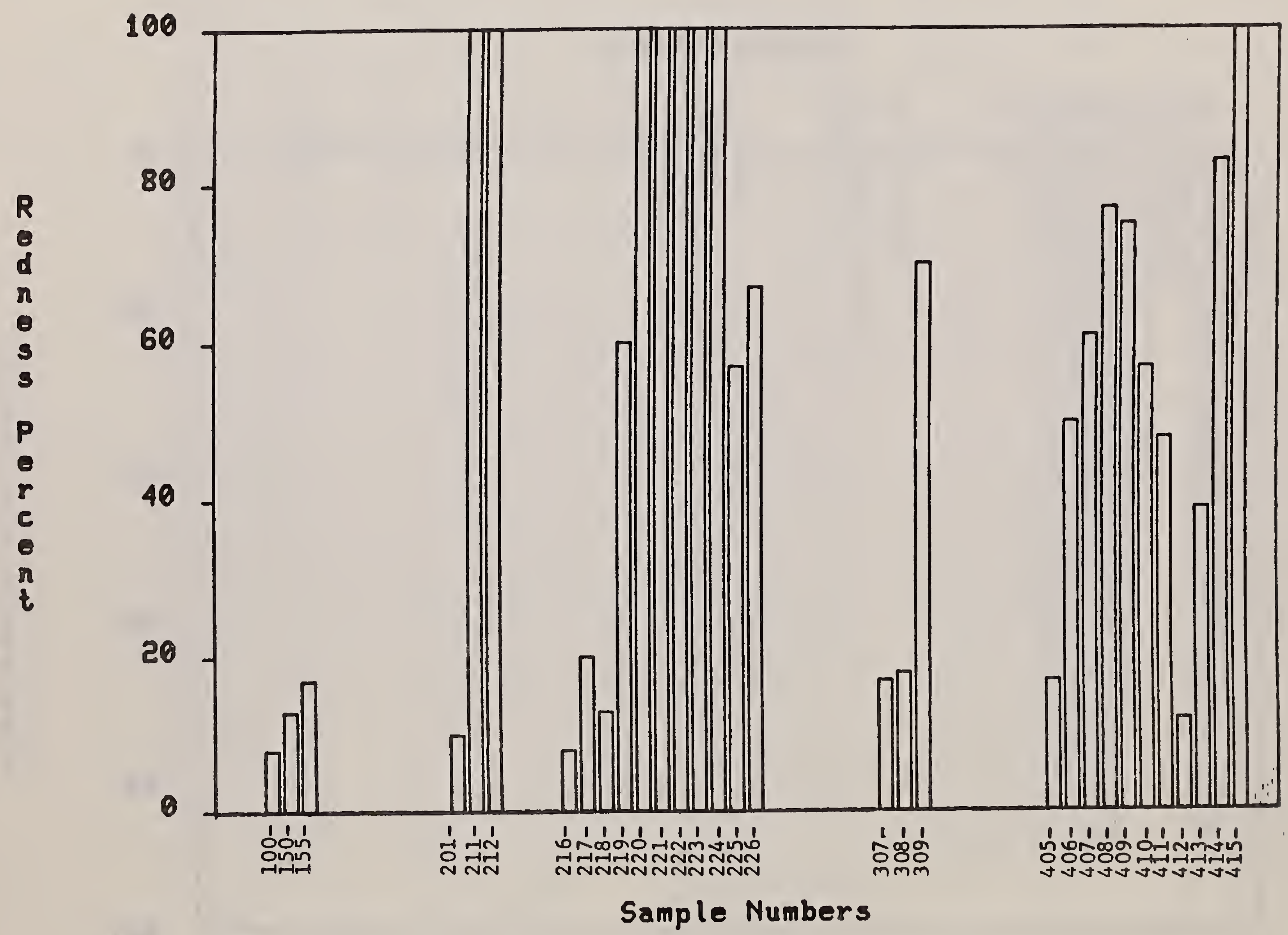


Figure 7. Percentage of trials in which designated color samples were identified as red under HPS

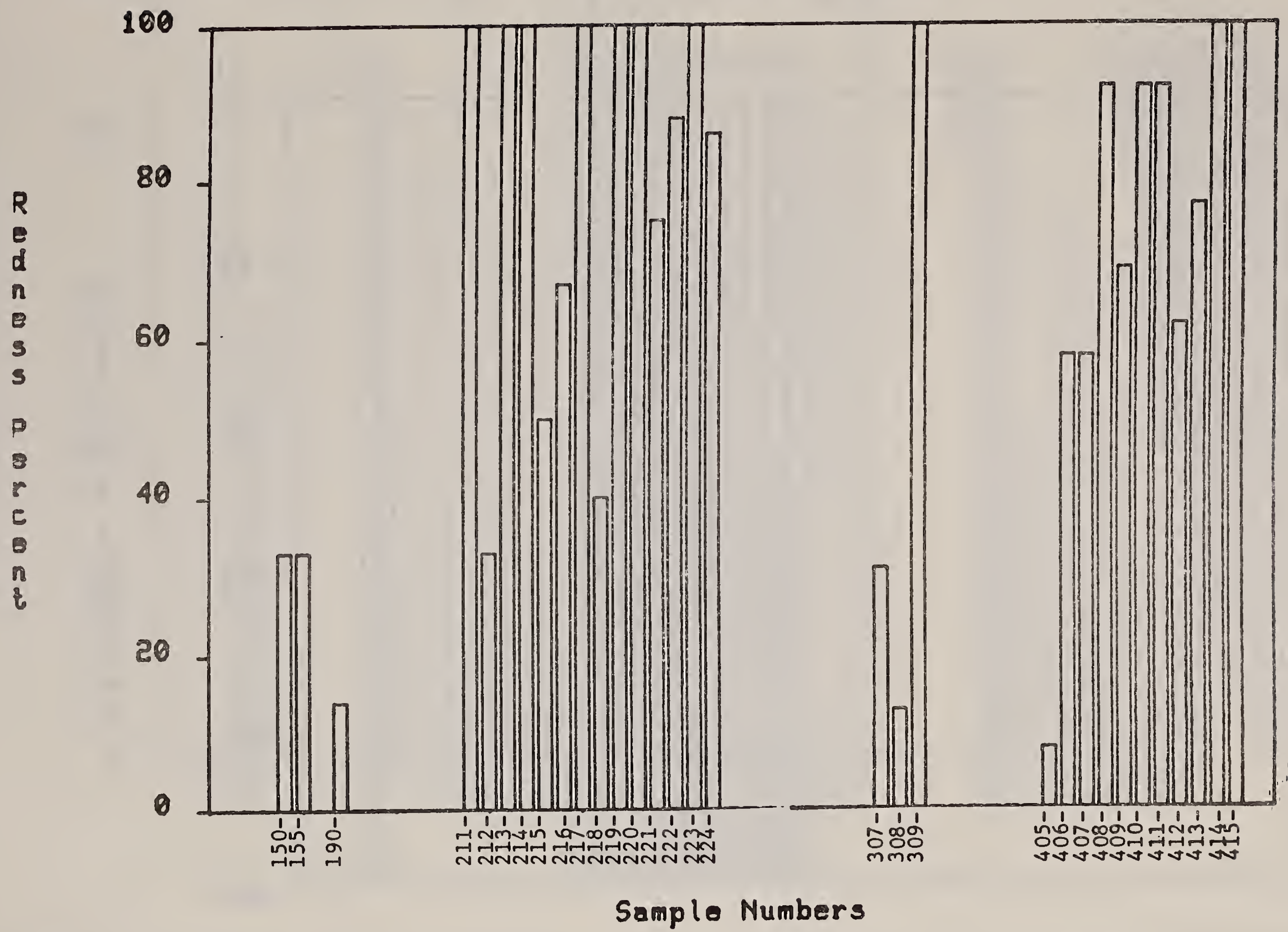


Figure 8. Percentage of trials in which designated color samples were identified as red under MH

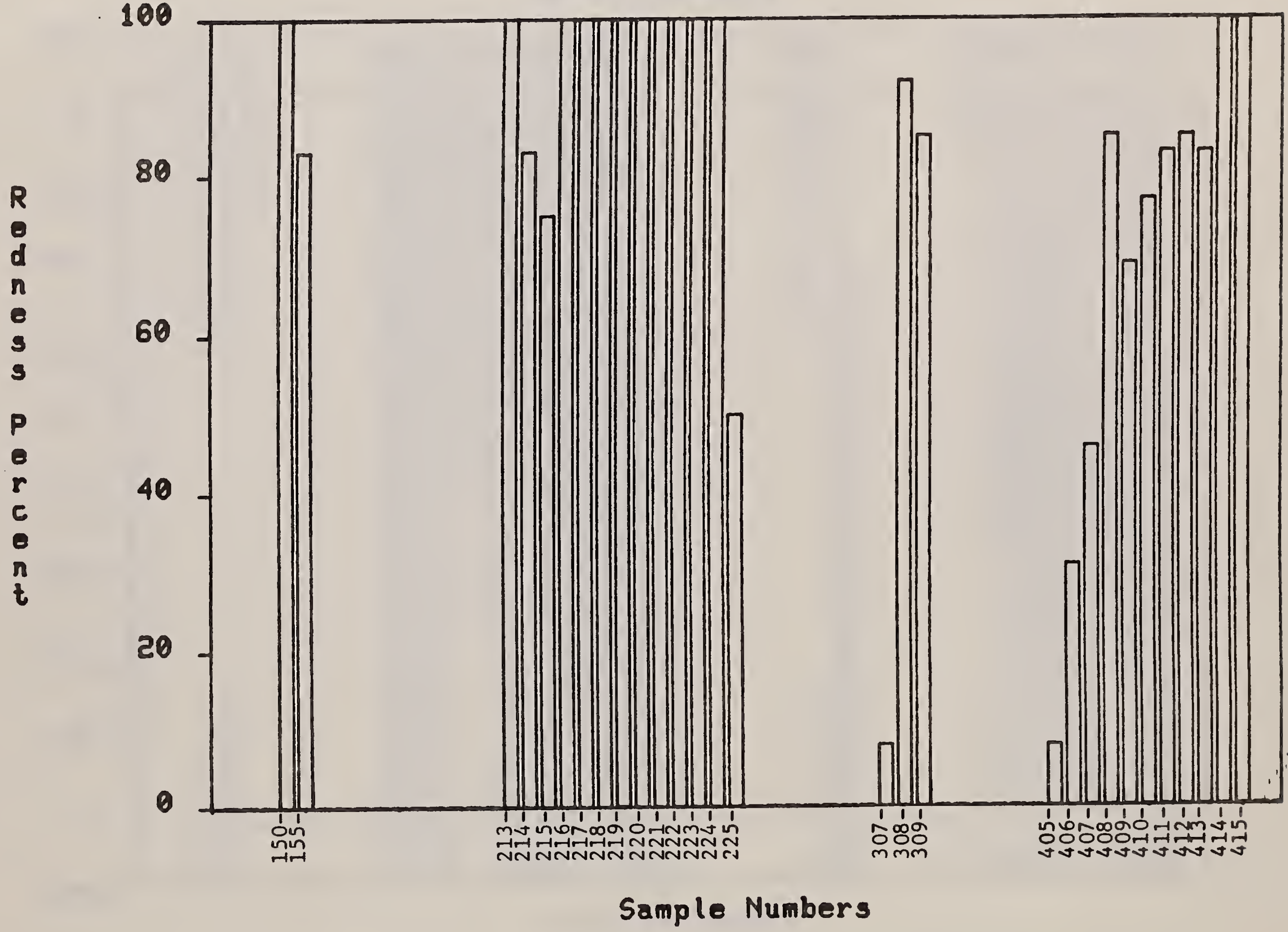


Figure 9. Percentage of trials in which designated color samples were identified as red under fluroescent

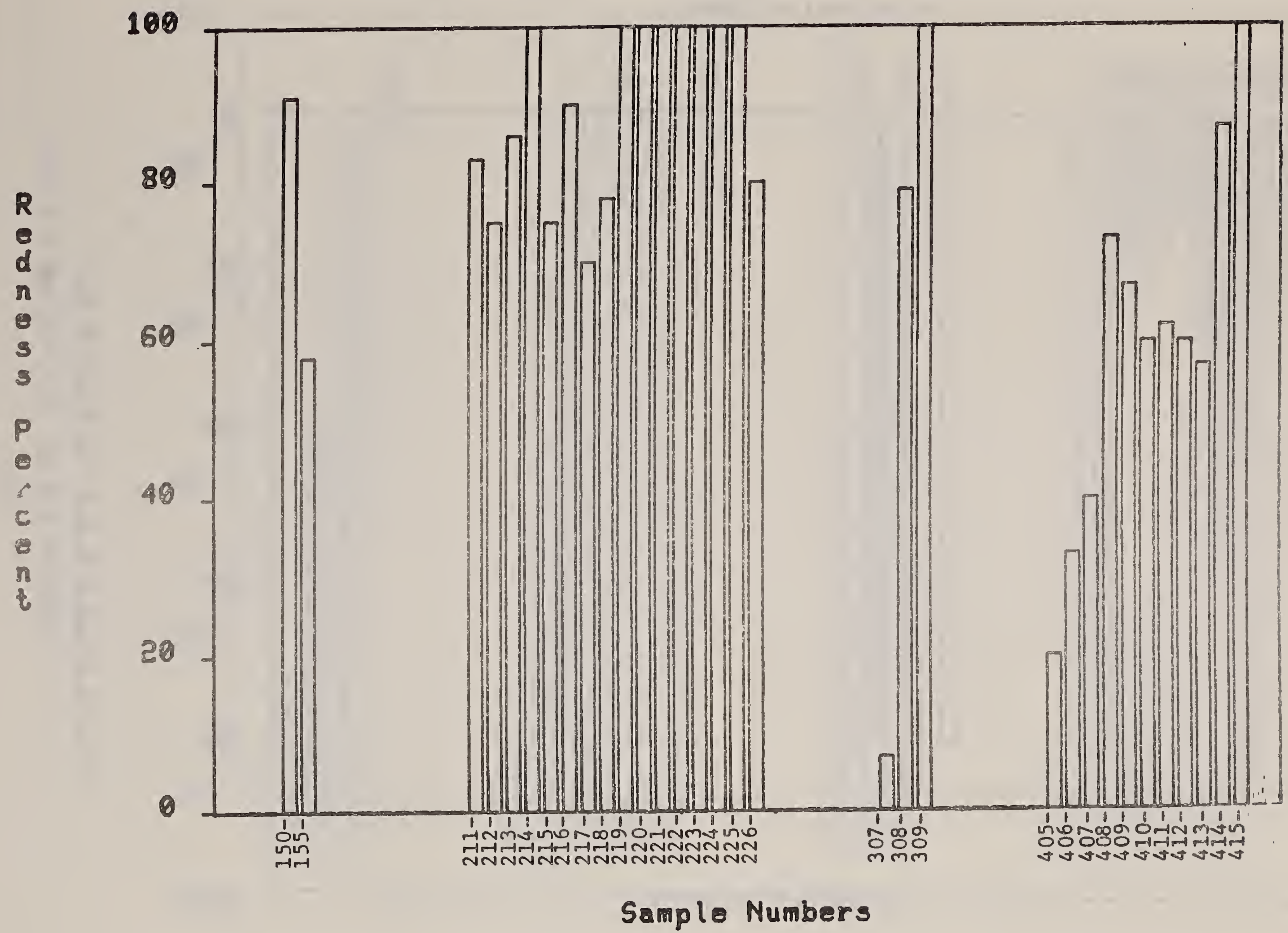


Figure 10. Percentage of trials in which designated color samples were identified as red under tungsten

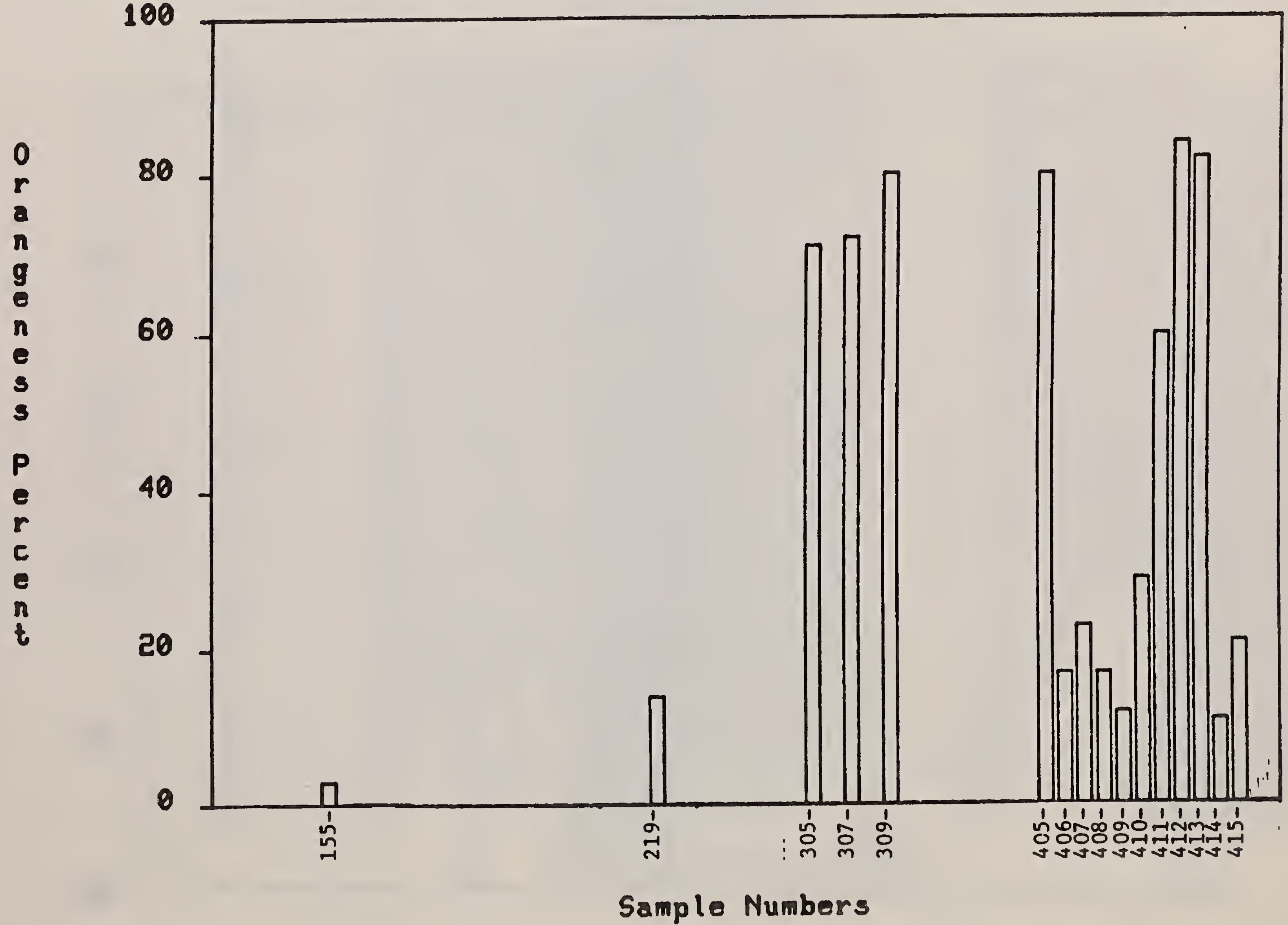


Figure 11. Percentage of trials in which designated color samples were identified as orange under LPS

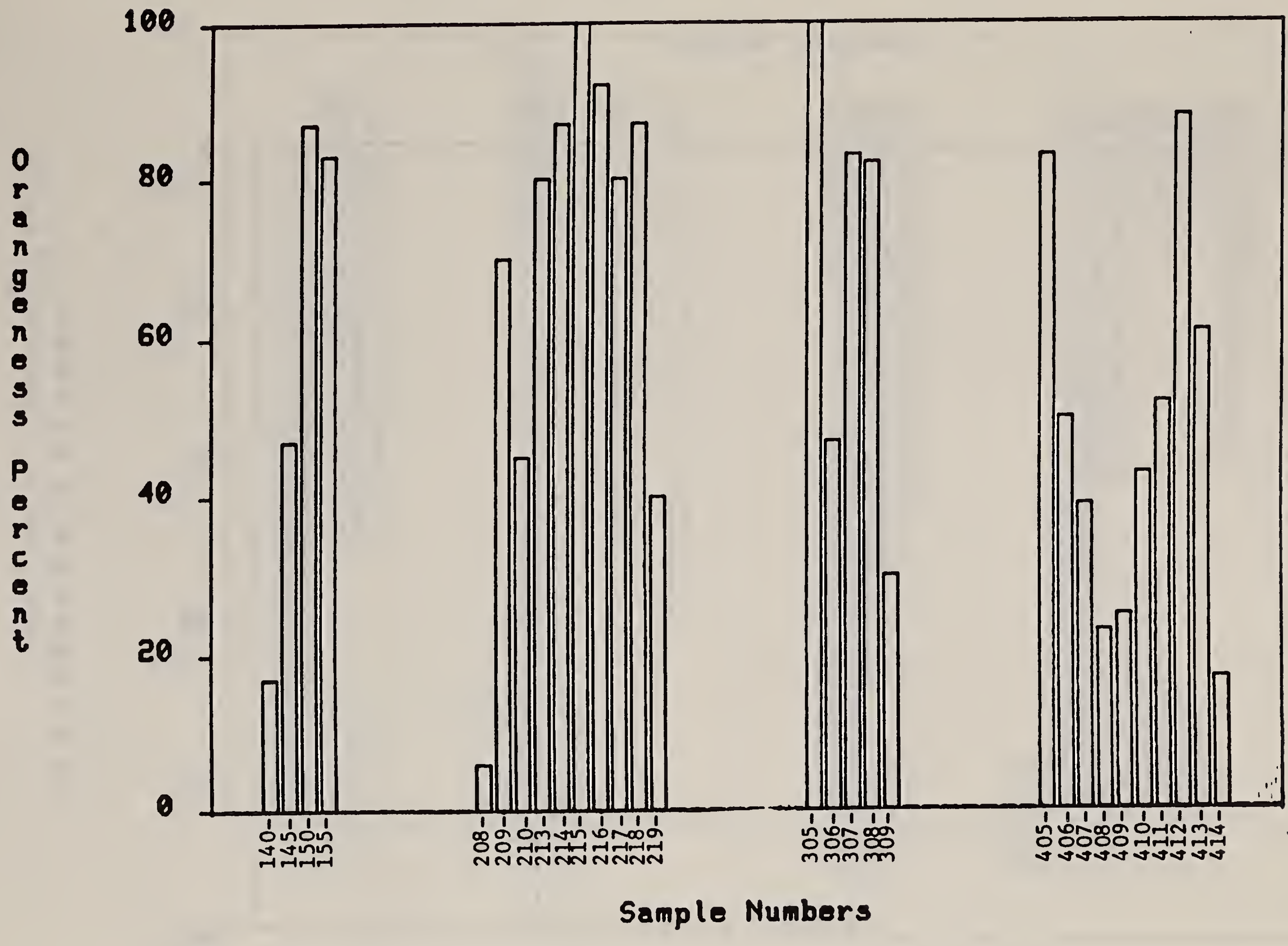


Figure 12. Percentage of trials in which designated color samples were identified as orange under HPS

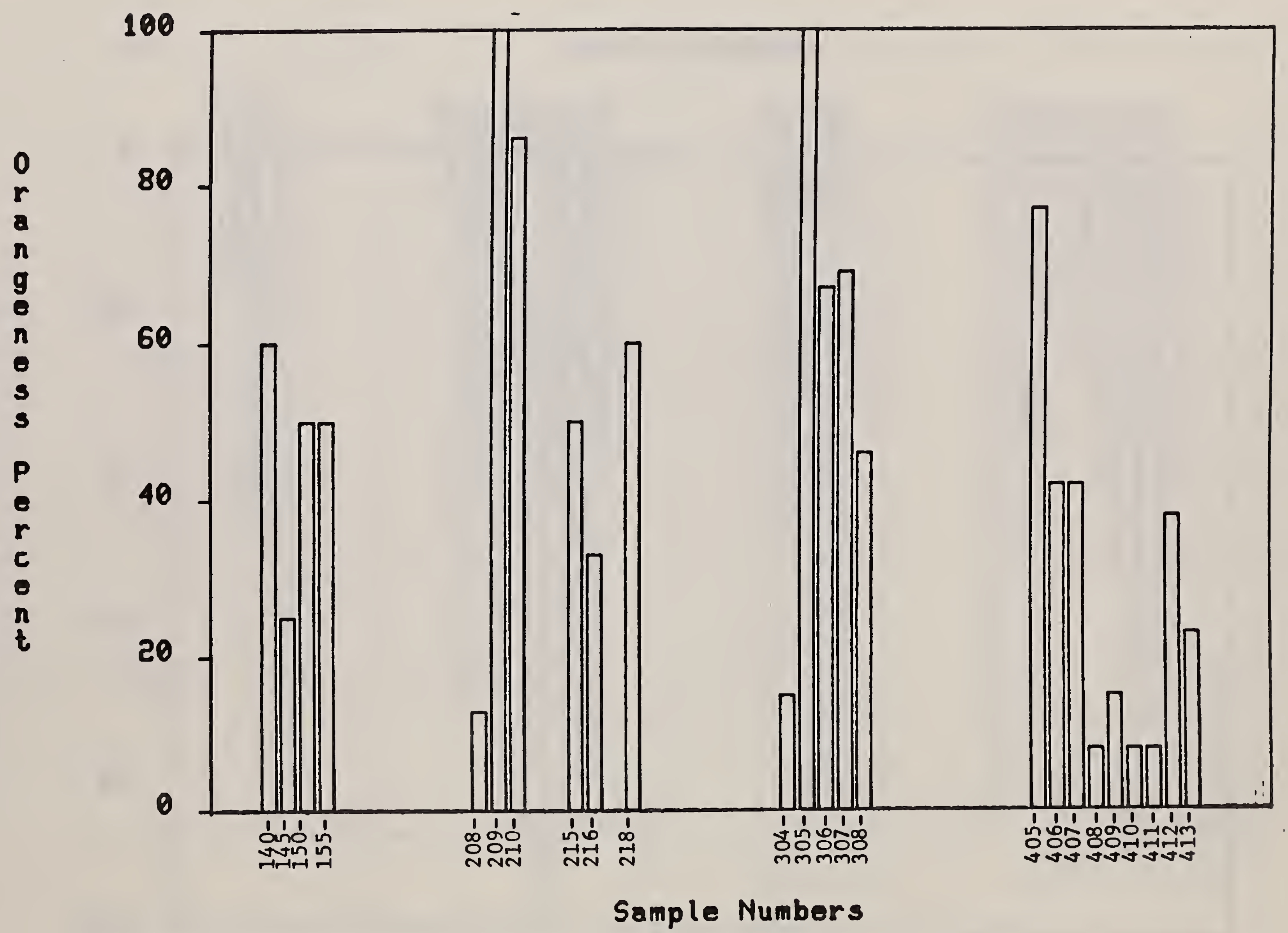


Figure 13. Percentage of trials in which designated color samples were identified as orange under MH

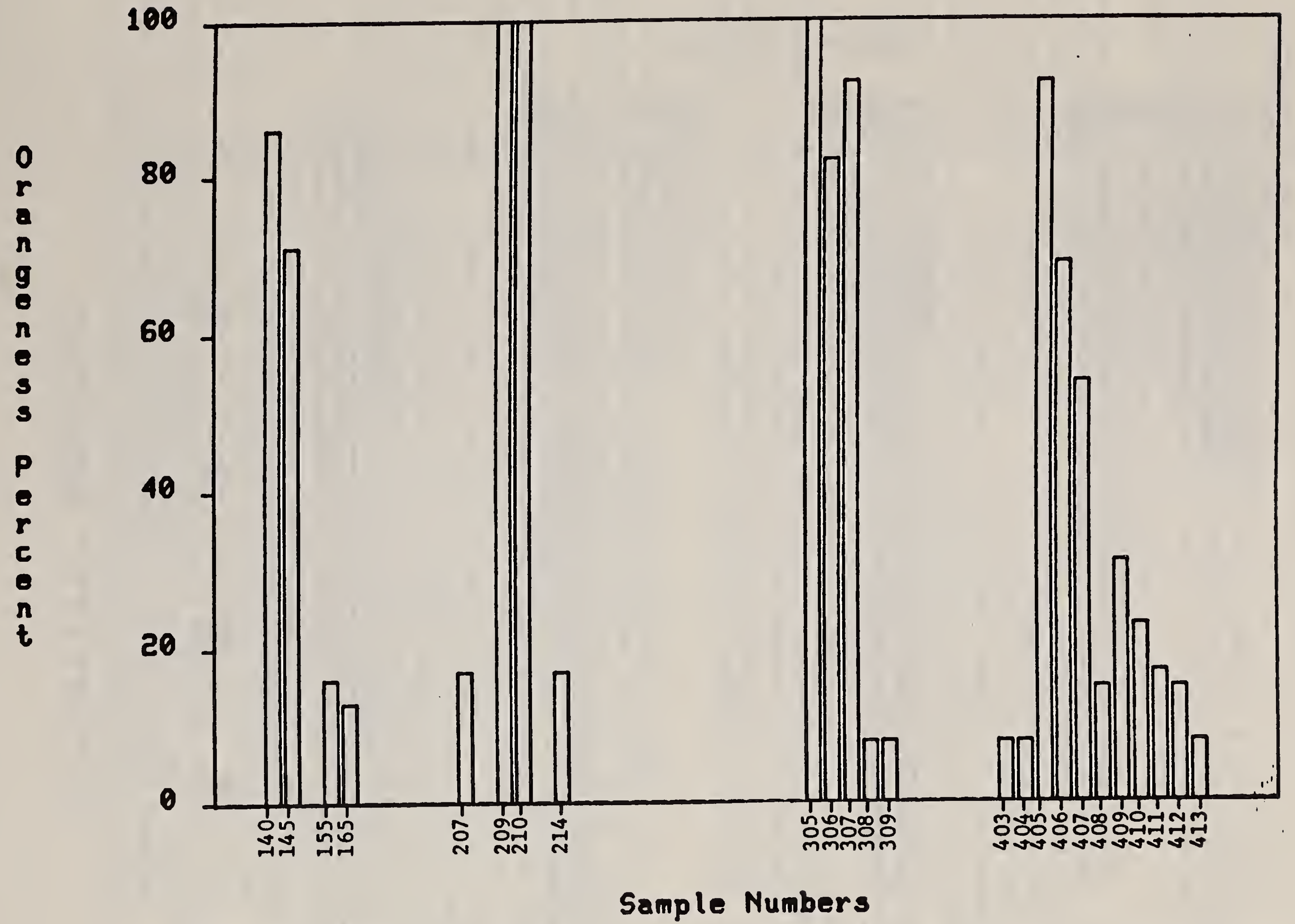


Figure 14. Percentage of trials in which designated color samples were identified as orange under fluorescent

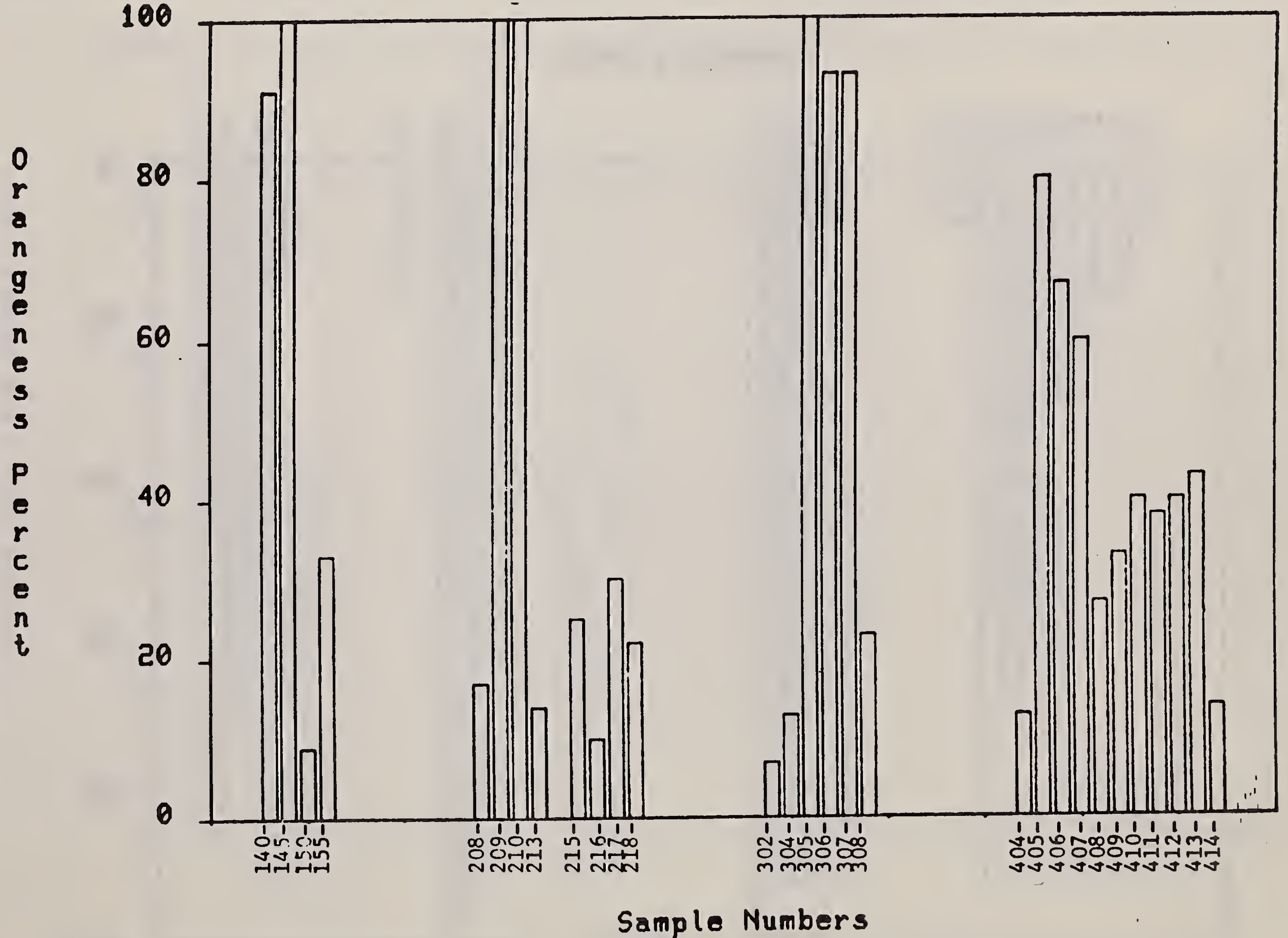


Figure 15. Percentage of trials in which designated color samples were identified as orange under tungsten

for orange. Because fewer color samples were studied for other safety colors such as blue and green, these data were left in tabular form, and can be examined in tables 5 to 8.

4.2 COLOR SHIFT DATA

It is also of interest to determine how the color names for a given sample shifted as a function of the light source. Figures 16 to 19 compare the color name given for each sample under each light source with the name given under tungsten light.

Tungsten (incandescent) lamps represent the source with the highest color-rendering index used in the present experiment. (It should be noted that for "warm" light sources with a correlated color temperature below 5000 K, the reference source in the definition of the color-rendering index (CIE, 1974), is a blackbody or Planckian radiator. The spectrum of an incandescent lamp is close to that of a blackbody radiator, so that these lamps have color-rendering indices close to 100.) As a result, the appearance of a color under the tungsten source is the best indication (in the present experiment) of the "true" or "correct" color of a sample. Thus, deviations from a color's appearance under tungsten would be largely classifiable as a distortion.

Figure 16 presents the shift data from tungsten to LPS; figure 17 presents the shift data from tungsten to HPS; figure 18 presents the shift data from tungsten to MH; and figure 19 presents the shift data from tungsten to fluorescent. These figures enable one to determine the kinds of color shifts and confusions that occur for a particular sample color relative to tungsten as different light sources are used.

To construct these figures, only the dominant color name was used. If 50 percent or more of the responses given were for one color name, this was considered as the dominant name and included in the color shift plots. Fewer than 50 percent responses for one name meant that that sample was excluded from the color shift figures, as having an ambiguous color, not plottable on the diagram. Samples that were excluded on this basis are listed on the figures. Note that these figures are analogous to correlation scatter plots. Perfect agreement between a source and the reference (tungsten) source in the color names used would be indicated in these diagrams if all the sample numbers in the body of the table were located along the main diagonal (upper left to lower right). Otherwise, the more scatter away from this diagonal, the more disagreement in color name between the source and the tungsten light.

Figure 16 indicates that extensive shifts in color names occurred from tungsten to LPS. The majority of the color names shifted toward yellow under LPS. Furthermore, in no case were purple, green, white or gray, seen as such for any sample series under LPS. This figure demonstrates the extensive color distortions that occurred for LPS light relative to tungsten. Aside from fluorescent oranges and reds, which can be seen as such under LPS, all other colors are seen as varying only in the light-dark dimension. Most observers labeled light colors as yellow and dark colors as brown, although sometimes they used gray and black instead. As a rule, white, yellow, and fluorescent

Shift Charts

Tungsten to LPS

	LPS									
TUNGSTEN	PURPLE	BLUE	GREEN	YELLOW	ORANGE	RED	BROWN	BLACK	GRAY	WHITE
Purple							201, 202			
Blue		300							115 203, 204	
Green		301		205, 206 303 400, 401 402					120, 125	
Yellow				130, 135 207, 208 304, 403 404						
Orange				140, 145 209, 210 306	305, 307 405	406, 407				
Red				211, 212 213, 215 218 309	411, 412 413	408, 409 410, 414 415	220, 221 222	223, 224 225, 226		
		<u>Excluded</u>								
Brown		100, 105 150, 155 165 201, 202 214, 216 217 219, 302					160			
Black		110						170		
Gray				180, 185						
White				190, 195 310						

Figure 16. Color shift data -- tungsten to LPS
A comparison of color names given for
each sample under both tungsten and
LPS light

Shift Charts

Tungsten to HPS

TUNGSTEN	HPS: PURPLE	BLUE	GREEN	YELLOW	ORANGE	RED	BROWN	BLACK	GRAY	WHITE
Purple	100, 105 201, 202									
Blue		110, 115 203, 304 300								
Green		125	205,206 302, 303 401, 402	400						
Yellow				130, 135 207, 208 304, 403 404						
Orange				140, 145 209	305, 306 307, 405	407				
Red					150, 155 213, 214 215, 216 217, 218 308, 411 412, 413	211, 212 219, 220 221, 222 223, 224 225, 226 309, 408 409, 414 415				
Brown							160, 165			
Black								170, 175		
Gray			<u>Excluded</u> 155 210 301						180, 185	
White			306 406							190, 195 310

Figure 17. Color shift data -- tungsten to HPS
A comparison of color names given for each sample under both tungsten and HPS light

Shift Charts

Tungsten to Metal Halide

TUNGSTEN	Metal Halide									
	PURPLE	BLUE	GREEN	YELLOW	ORANGE	RED	BROWN	BLACK	GRAY	WHITE
Purple	100, 105									
	201, 202									
Blue		110, 115								
		203, 304								
		300								
Green			120, 125							
			205, 206							
			301, 302							
			303, 400							
			401, 402							
Yellow				130, 135						
				207, 208						
				304, 403						
				404						
Orange				145	140, 209	406, 407				
					210, 305					
					306, 307					
					405					
Red	225, 226				218	211, 415				
						213, 214				
						216, 217				
						219, 220				
						221, 222				
						223, 224				
						309, 408				
						409, 410				
						411, 412				
						413, 414				
Brown							160, 165			
Black								170, 175		
			<u>Excluded</u>							
									180, 185	
Gray			150							
			155							
			212							
			215							
White			308							190, 195
			310							

Figure 18. Color shift data -- tungsten to MH
A comparison of color names given for each sample under both tungsten and metal halide light

Shift Charts

Tungsten to Fluorescent

TUNGSTEN	Fluorescent: PURPLE	BLUE	GREEN	YELLOW	ORANGE	RED	BROWN	BLACK	GRAY	WHITE
Purple	100, 105 201									
Blue		110, 115 203, 304 300								
Green			120, 125 205, 206 301, 302 303, 401, 402							
Yellow				130, 135 207, 208 304, 403 404						
Orange					140, 145 209, 210 306, 307 405, 406 407					
Red	211, 212 226					150, 155 213, 214 215, 216 217, 218 219, 220 221, 222 223, 224 308, 309 408, 409 410, 411 412, 413 414, 415				
Brown							160, 165			
Black								170, 175		
Gray			<u>Excluded</u> 225 310 400						180, 185	
White										190, 195

Figure 19. Color shift data -- tungsten to fluorescent
A comparison of color names given for each sample under both tungsten and fluroescent light

yellow are completely indistinguishable under LPS, even in lightness. The blue appearance of samples 300 and 301 is difficult to explain, but they evidently appeared primarily black with a blue tint. In addition, figure 4 shows that a very small amount of energy at 400 nm was present in the LPS spectrum. The blueness may have arisen from this band.

By comparison, the shifts in color name from tungsten to HPS presented in figure 17 were far less extensive. There was a shift from red toward orange, as well as a shift from orange and one from green toward yellow, but generally the shifts in color name were far less extensive than those occurring under LPS. It is important to remember that these and all other shifts in these figures are general trends. The appearance of a "red" (or other color) under any light source depends on the particular pigment or dye used to produce that color. By choosing the right specific red or orange pigment, the probability of correct identification under HPS and other sources can be greatly increased.

Figure 18 demonstrates an even greater reduction in color shifts for metal halide. Unlike either LPS or HPS, a few shifts from red to purple occurred, as well as a shift of one sample from orange to yellow. Generally, however, the color names given to samples viewed under metal halide illumination were the same ones given under tungsten.

Figure 19 compares color names given under fluorescent light with those given under tungsten. The only shift which occurred under this light was for certain 200 series samples which shifted from red to purple. Otherwise the color names were the same.

Originally, because of the special safety significance of the red-to-orange range of colors, it was intended to regard red/orange and orange/red as separate naming categories, distinct from red and orange. A consequence of this provisional arrangement, however, was that the entire range of samples from 404 to 413 was excluded from the color-shift figures, under the 50 percent rule. As a result, the final decision was to treat the orange/red categories like all other names with secondary components; namely, to merge them with the primary name category. Thus, tables 5 to 8 present the frequency responses for red/orange and orange/red in parentheses, but the former namings are included in the total count for red, and the latter in the total count for orange, in tables 5 to 8 and figures 6 to 19.

In these figures, it should be noted that for the sample series 403-415, for all light sources, there is a marked tendency to call these samples both orange and red. Although each sample is responded to with one or the other of these color names more than 50 percent of the time, in very few cases is that name applied anywhere near 100 percent. Thus, for this series, nominal orange and red are often confused with each other. A similar distribution of color names occurs for samples 307 and 308, and to a somewhat lesser extent for 215/ 216, and 150/155. The marked confusions in color name between many of the red and orange samples, regardless of light source, raises issues that will be addressed in the Discussion section. Here, it will suffice to point out that the fault for any such confusions can lie with either the light sources, or with the samples themselves.

5. DISCUSSION

5.1 RECOMMENDATIONS BASED ON SAFETY COLOR RESEARCH

The data presented in the Results section suggest that a set of colors can be selected from among the four sample series which are more unequivocally recognizable under all illuminants than the current ANSI Z53 standard safety colors. Further research is desirable before this selection of colors can be regarded as definitive; however, the research to date supports the idea that a set of highly identifiable colors can be specified. This set could include colors such as sample 301 for green, sample 300 for blue, sample 130/135 for yellow, sample 305 for orange, and sample 414 for red. Of all the samples studied, these were the most frequently correctly recognized under all 5 sources. It should be pointed out, however, that the recommended green, as well as any other green color sample, was not recognized as such under LPS. The suggested green has the advantage of confusions with innocuous gray rather than yellow (signaling caution) under LPS. Use of a fluorescent green is not effective for LPS because the rule for everyday fluorescence is that the stimulating wavelength must be shorter than the wavelength of the re-emitted (fluorescent) light. Since almost all the energy in the LPS spectrum is in a narrow band near 589 nm, in the yellow-orange part of the visible spectrum, such light can excite only longer-wavelength orange or red fluorescence. Consequently, obtaining green fluorescence under LPS appears out of the question, except possibly through unusual physical mechanisms.

Recommendations for purple, brown, gray, white, and black would, according to the experimental results, follow the existing ANSI Z53 standard (samples 100/105; 160/165; 170/175; 180/185; and 190/195). Although these particular colors performed very poorly under LPS light, no other sample performed any better under this light source. (Very few other samples were studied for these colors.) Fortunately, these five colors serve primarily as background or outline colors in the ANSI system, rather than coding this kind of safety message. [Note that, because red is confused with black under LPS, red on black signs (or vice versa) would have very low legibility under this source; and yellow on white (or white on yellow) signs--never very visible at best--are unlikely to be legible at all under LPS. It should be recalled that under LPS, no distinction can be maintained between white and yellow, even fluorescent yellow. Because the whole environment appears yellow, it may be inadvisable to use yellow in its traditional role of signaling caution, under LPS. Orange (fluorescent) is available for this role, if another degree of warning short of the danger message of red is desired for this light source.]

It is of interest that three of the colors in the suggested set are from the 300 series--that is, they are retroreflective, and sample 305 is also fluorescent. There is no obvious reason why the retroreflective property of these samples should have been of value in improving color recognition, since the illumination was essentially diffuse and the retroreflective component of the light reaching the subject's eye was presumably very small. Thus, it can be tentatively assumed that it was the specific colorants (pigments or dyes) used in these 300-series samples that made them so recognizable. It is not reasonable that the special requirements of retroreflective materials would necessitate the

use of colorant formulations differing from those responsible for the colors of the other three series of samples. It must be stressed that even colors that appear identical under daylight or incandescent light may appear different under other light sources (the phenomenon termed metamerism), as long as the samples have significantly different spectral reflectance curves; i.e., if the colors of the samples arise from different pigment or dye mixtures, or if one color is due to a pigment and the other to a chemically distinct dye. Evidently, the particular colorants used in samples 300, 301, and 305 are better, in terms of stability of color appearance under changes of light source, than are any of the approximately corresponding colorants in the ordinary and pure-fluorescent samples. Future experimentation is advisable in which non-retroreflective samples prepared from these same colorants are tested. Such samples could be equally as identifiable as the retroreflective ones and might be cheaper to prepare.

In general, another experiment would be desirable to determine that the five key color samples listed above are accurately recognized under different illuminants (including ones not included in this study) by a larger group of subjects--more representative of the workplace population--and to confirm that these colors are not confused with each other. It will also be appropriate in the future to test other colors, since samples which are superior in stability of appearance to those suggested by this study may already exist, or may be developed.

Another factor to consider is that the viewing conditions used in the present experiment were deliberately chosen to represent a worst-case situation: i.e., the colors were presented in an environment with no other chromatic information. In the future, it would be informative to repeat the study with more commonplace viewing conditions--either in the field or in a laboratory situation. In both cases, a number of familiar colored objects could be in view throughout the experiment. It would be expected that under such conditions, correct identifications under all light sources, with the likely exception of LPS, would improve.

The confusion between orange and red obtained with samples from both the 300 and 400 series, suggests that it is difficult to formulate an orange that is never called red, or a red that is never called orange. Furthermore, this pattern of confusions occurs across all light sources. In addition, of course, under each separate light source, specific red samples will shift toward orange and vice versa, thus complicating the picture even further. It would not be proper to conclude, however, that these red-orange confusions are due in every case to the light sources used in the experiment. Two much more likely causes can be pointed out. First, the basic, "unique" hues of color perception are red, yellow, green, and blue. Orange is a mixture of red and yellow, and accordingly can be expected to resemble red (or yellow) considerably more than yellow resembles green, green resembles blue, or blue resembles red. Thus, red and orange intrinsically resemble each other more than most of the other pairs of colors studied. Secondly, a substantial number of the red samples tested were known in advance to be somewhat orangish. ANSI Red was deliberately chosen to be on the orange side, because that choice makes it easier for one

class of red-green color-defective observers (the protans) to distinguish the red from black. In addition, most fluorescent red pigments, for physical reasons tend to be somewhat orangish. (It should be noted that the Coast Guard (1980) in its specification for fluorescent colors does not even attempt to distinguish fluorescent red and orange, but instead defines a single fluorescent red-orange color.) Therefore, the many red-orange confusions found in the present experiment may well be attributable to the particular samples used, and to the perceptual similarity of any red to any orange.

Confusions between safety colors other than red and orange were not nearly so marked, and tended to be more specific to a particular source. Thus, under all sources, colors called yellow under tungsten light were rarely seen as orange and almost never as red. Yet, colors called orange under tungsten were fairly often called yellow under both LPS and HPS, and occasionally under metal halide. These data suggest that the current use of red and yellow to indicate two different degrees of hazard is practical under a variety of light sources, with a judicious choice of the red and the yellow. Proposals to use red, yellow, and orange to indicate three levels of hazard appear likely to prove unworkable because such fine color discriminations cannot always be maintained. Indeed, table 5 reveals that even under more than 30 fc (vertical) of tungsten light--essentially perfect in color-rendering index--the current ANSI Red was called orange 5 out of 22 times, and the ANSI Orange was called yellow 1 out of 19 times. No such confusions were seen for ANSI Yellow under tungsten light.

5.2 SUPPORTING RESEARCH

Jerome (1977) pointed out the possibility of confusions between the various ANSI Safety Colors when viewed under some high-intensity discharge (HID) lights. He commented that "The ANSI safety colors were designed, and very carefully specified, to be uniquely identifiable at all times. This identification is intended to be possible without any other clues, i.e., it must depend only on the identifiability of the single colors viewed alone" (Jerome, 1977, p.180).

Jerome asked 20 observers to indicate the primary color (no secondary color allowed) of a set of safety colors (the 100 series from the present study) under each of six lamps (daylight fluorescent, incandescent, metal halide, deluxe mercury, clear mercury, and high pressure sodium). Low pressure sodium was not used because the author concluded that all ordinary colors seen under this source were confused, and that any color differences were due to lightness differences. Sample illuminance was quite low, 0.5 fc, much lower than in the present experiment. Jerome chose this level because it is the minimum specified level for emergency lighting. Jerome calculated the percentage of correct identifications and confusions for each safety color. He found that major confusions arose for both types of mercury lamps and high pressure sodium. As in the present study for the 100 series, under HPS ANSI Red and Orange were confused with each other and ANSI Green was often seen as blue. Under metal halide, safety Red was often confused with orange. (In the present study, ANSI Red (150/155) could not be given a dominant color name under metal halide, because of extensive confusions between orange and red, plus occasional responses of yellow and brown.) Jerome also found a few red-orange confusions

for incandescent light--confusions that also arose in the present study. Thus, in general trends, Jerome's data certainly support those from the present study.

Where detailed differences arose, such as greater confusions in his study between blue and black or white and yellow, they may well be due to the very low illumination level used by Jerome, as well as his use of a different set of light sources.

"The net conclusion is that there are some light sources being used extensively under which the [current ANSI standard] safety colors cannot be identified positively with any degree of certainty. Under these circumstances, if the safety colors are to perform their assigned function, supplementary lighting must be provided for the colors under which their identification can be determined without ambiguity" (Jerome, 1977, p. 182). A comparison of the calculated CIE color rendering index for the samples under the various light sources, with the percentage of correct identifications, indicated very poor correlation between the two measures. Jerome (1977, p. 182) commented that "Apparently, the answer is not how faithfully the colors are rendered, the attribute indicated by the Color Rendering Index, but how well the colors can be perceived as different from the other colors. That is, if the red can be identified as red and not some other color, even though it may differ greatly from its daylight appearance, it is performing its function as a safety color satisfactorily."

To deal with the problem of safety colors under HID or other illuminants, Thornton (1977) proposed that the colors themselves, rather than the lights, should be redesigned. He asked: "How can we redesign the safety-colors for maximum stability of perceived color with change of illuminant; i.e., so that all present and future commercial lamps have the best chance of rendering the safety-colors so they are easily and correctly identified?" (Thornton, 1977, p. 93). He suggested that the best way to achieve the redesign was to alter the spectral reflectance distributions of the safety colors, by using fluorescent colors for red, yellow, orange, and purple samples. This approach was taken for the series 400 colors in the present experiment, as well as for some of the 300 series. (No fluorescent purple sample was acquired, however.) Of course, in addition to the safety colors, the illuminant itself could be modified to allow maximum color discrimination capability (Thornton, 1977).

Boyce and Simmons (1977) investigated the effects of light source and illuminance level on a much finer hue-discrimination task. Using the Farnsworth-Munsell 100-Hue test, they measured hue discrimination performance under a variety of light sources. These sources were, however, primarily fluorescent sources, so that no data was obtained for HID sources such as metal halide, LPS, or HPS. The 100-Hue test consists of 85 colored discs arranged in approximately equal perceptual steps, around the complete hue circle, with constant saturation and lightness. Lamp type, but not, in general, illuminance level, was found to affect performance significantly. Age, but not experience with the 100-Hue test, was also found to affect performance significantly, with those over 55 making significantly more errors. The authors concluded that while age may determine the general level of errors,

there is also an indication that for older subjects, performance is better at higher illuminance levels. The error scores indicated that lamps with "poor color properties" produce more errors than those lamps with "good color properties". The choice of light sources as well as the age of the observer determines the discriminability of colors far more than did the illuminance level or observer's experience. This study, although it did not use the high or low pressure sodium lights demonstrated to cause problems in color rendition in other experiments, did demonstrate that variations in the illuminant alone impair performance on the 100-Hue test.

Another study by Ronchi and Stefanacci (1978) also assessed performance on the 100-Hue test under HPS light. It demonstrated that errors increased under HPS relative to illuminant C at 70 lux and that these errors were similar to those exhibited by color deficient observers. A tritan-like effect occurred under HPS for about one-half the subjects and a mixed protan/deutan effect for about one-third. See figure 1 parts a, b, and c for examples of each type of confusion and section 2.3 for definitions.

The studies which have assessed color discriminability under various light sources have demonstrated a clear decrement in performance, especially for HPS and LPS. Results from the present study suggest that use of fluorescent and retroreflective-fluorescent colors may increase correct color identification particularly for the red and orange colors under all sources, and for blue and green under all sources except LPS. These results bear out the recommendations made by Thornton (1977) that modification in the safety colors themselves may be one of the best ways to ensure their discriminability.

6. RECOMMENDATIONS

6.1 APPLICATIONS TO THE WORKPLACE

The results of the present experiment combined with those by Jerome (1977) and the suggestions by Thornton (1977) indicate clearly that use of the current ANSI Safety Colors under some HID light sources is not advisable if accurate color recognition is desired. Two solutions suggest themselves: modify the lighting, or modify the spectral distribution of the safety colors themselves, by using fluorescent pigments or dyes (such as those used in the fluorescent 400 series, or in the retroreflective-fluorescent 300 series samples). Using the latter approach in the present study, a set of highly identifiable colors was isolated for further study. These colors appear to be discriminable under a wide variety of HID and other lamps, including partial discriminability even under LPS.

If conventional ANSI Safety Colors are to be used, the use of LPS as the light source is not recommended, as most of the current safety colors are not identifiable under this source. If the decision is made to continue using the conventional ANSI Safety Colors, then the LPS or other poor color-rendering lighting system should be modified, at least for critical signs. There are a number of possibilities in this approach. The first, which is perhaps the easiest way to ensure good color recognition, is to switch the lamps to ones with good color rendition. With this approach, cost becomes a factor, as good color rendering sources are often more expensive to operate. The second alternative is to mix luminaires using both good and poor color-rendering sources over an entire area. While this solution will be less expensive than the first, the best mixtures of illuminants for accurate color recognition combined with good energy efficiency (luminous efficacy) is not presently known. A third possibility is to add a small, supplementary, good color-rendering source directly over the sign itself. This localized lighting will illuminate the safety sign itself, and facilitate accurate color recognition. It does, however, require either a battery or an electric power outlet near the sign. In many cases, it may be advantageous for color recognition to shade the sign at least partially from the color-distorting general lighting. The final possibility is the use of powered, self-luminous signs. Such signs are widely used for conventional exit signs; their use could be extended to signs warning of highly hazardous conditions. The use of localized lighting or self-luminous signs appears to be a reasonable solution in areas where general LPS or any very poor color-rendering lighting source is already installed. This alternative also appears to be the only means of ensuring that green is recognized as green under LPS light, since all green color samples were poorly recognized under LPS in the present study.

6.2 PROBLEMS OF COMPLIANCE

If the current ANSI Safety Color Standard, Z53.1 (1979) were to be revised to specify the set of color samples currently identified as being most recognizable under all sources in the present experiment, how would a safety officer in a workplace determine whether colors in that workplace complied with the new standard? One might think of using a small, inexpensive colorimeter, to do

this job. Unfortunately, at this point the experimental set contains both retroreflective and fluorescent colors, both of which are very difficult to measure under non-laboratory conditions. The reader is referred to Billmeyer (1979) for a discussion of the procedures to follow when measuring fluorescent colors and calculating spectral total radiance factors under daylight illumination. The reader is referred to Eckerle (1980) for a discussion of the accuracy of measurements of retroreflective colors, as well as the present inadequacy of field-measurement methods.

An even simpler idea would be to produce a set of color tolerance charts for the new colors, analogous to the U.S. Department of Transportation's Hazardous Materials Label and Placard Color Tolerance Charts (1973), which performs this role for the current ANSI Safety Colors. Theoretically, no set of color tolerance charts is a valid compliance device if the on-site illumination differs significantly in its spectral power distribution from the light source for which the charts were standardized. However, if it can be agreed that the set of colors suggested by the present experiment appear correct under any of the current commercial sources (with appropriate exceptions for LPS), then a set of color tolerance charts might be feasible. The chart colors would all look somewhat different under each source, but with the chart colors and the workplace colors all illuminated by the same source, it would be reasonable to allow the color under test to be in compliance if it lay visually within the range of the limit colors on the chart. Developing the limit colors for such a chart is a major project. The limit colors would have to be composed of different proportions of the same pigments or dyes as the standard colors, to avoid differential appearance-shifting with a change of light source (minimizing metamerism). Moreover, the determination of how far off from the standard color one should be allowed to deviate in hue, saturation, and lightness, would have to be made on the basis of careful color-naming experiments, such as the one reported here.

Since the concern in safety-color standardization is appearance (does the supposedly red color <u>look</u> red), one is forced to conclude that any valid compliance method possible at this time, if it is to apply uniformly to any source, must be based on visual judgments and cannot be instrumental, even if sufficiently accurate and inexpensive measuring instruments were available. This conclusion is a result of the phenomenon of chromatic adaptation, a significant factor for determining color appearance for people working under any light source. Figure 20 illustrates this point clearly. The five vertices of the pentagon locate the chromaticities of the current basic ANSI Safety Colors illuminated with HPS light. Note that <u>all</u> the chromaticities lie in what is normally thought of as the orange region of the chromaticity diagram, even that of ANSI Blue. [That point lies between the daylight (white) point and the orange part of the spectrum locus.] However, table 5 shows that ANSI Blue (sample 110/115) is <u>always</u> seen as blue under HPS, not as orange or anything else. To allow chromaticity (and reflectance) measurements by a machine to determine compliance with a color standard that applies to all sources, it would be necessary to determine through color-naming experimentation, the chromaticity limits that lead to each desired color perception <u>under adaptation to each separate light source</u>. This would require the gathering of a great

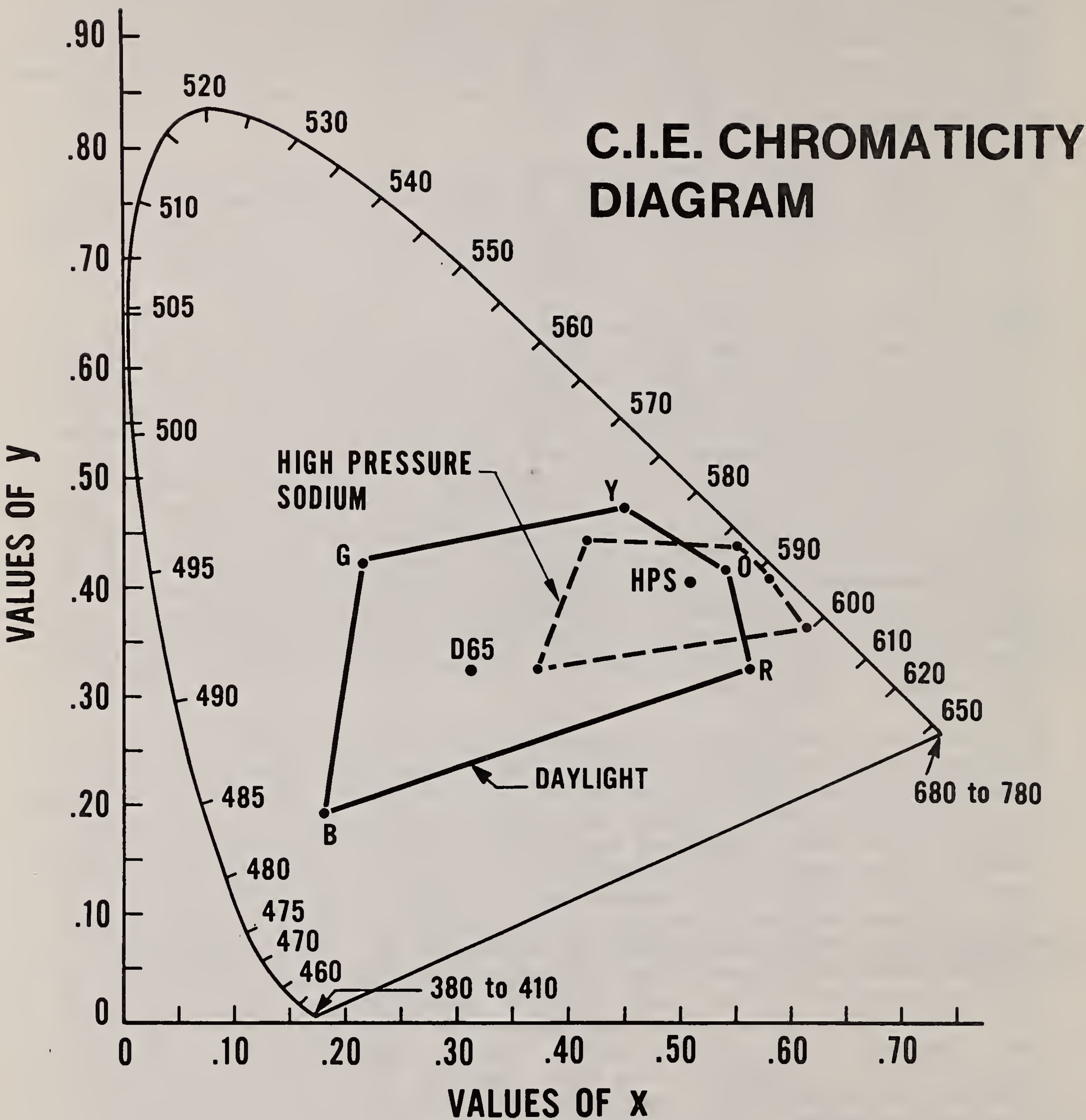


Figure 20. Chromaticities of standard ANSI colors illuminated with HPS light

deal of perceptual data, after which a set of many chromaticity-limit tables (one for each type of light source) would have to be supplied along with the measuring instrument.

6.3 RECOMMENDATIONS FOR FURTHER RESEARCH

One of the areas for which further research is needed has already been discussed but will be mentioned here again. This is the need to evaluate the performance of the set of safety colors identified as "most recognizable" from the present study, using a wider set of variables. This would include more observers, different illuminance levels, additional light sources (mercury, as well as any new sources), different adaptation times, and of course, any promising new color samples that have recently come into the market, such as new fluorescent colors or ordinary colors especially formulated to appear correct under HID sources. This experiment would determine if these samples are in fact effective under a wider set of controlled experimental conditions. This research should then be extended to field conditions, in which the discriminability and recognizability of signs using these colors in industrial settings would be assessed.

Another area in which further research is needed is that of chromatic adaptation. How long does adaptation to a monochromatic source, such as LPS last, and how great is the distortion in color recognition following exposure to such a source? If a person moves from an area lighted by one of these sources to an area lighted by another source, how accurately will the colors be perceived under the new source? Thus, both the time course and extent of chromatic adaptation need to be determined experimentally for different types of light sources. In addition, the magnitude of the distortion in color appearance due to chromatic adaptation should be determined for the color samples identified in this study.

An important long-range research project is the development of a formula for predicting the color appearance of any color sample under any light source, with no further necessity for perceptual experimentation whenever a new light source is marketed. Such a formula does not yet exist. Developing and validating this formula would require enormous amounts of perceptual experimentation, as well as of computer optimization of the constants for the formula, based on the perceptual data. Success, however, would mean predicting from the spectral reflectance curve of an arbitrary sample, and the spectral power distribution of an arbitrary source, the appearance that the sample would have if illuminated by that source and viewed by a person adapted to that source. The prediction might be in the form of the chromaticity (x,y) and luminous reflectance (Y) of a sample which has this same appearance when illuminated by and viewed under adaptation to a fixed reference source, such as the CIE daylight (D65) source.

The possibility of mixing sources which differ in their color-rendering capabilities has already been addressed, but the need to determine the optimum ratio of the source illuminances for a good balance between accurate color recognition and energy efficiency remains. Can an area be lighted primarily with LPS or similar poor color-rendering lights, to reduce lighting costs, with the addition of a few good color-rendering sources, and still allow good

color recognition? What is the optimum balance, in terms of total life-cycle cost of the lighting installation and color recognition? Again, a laboratory investigation is needed to determine, for each energy-efficient light source, the minimum proportion of the good color rendering light source needed to allow acceptable color recognition. If the proportion is too high, then the installation becomes too expensive, and defeats the use of the high-efficiency light sources. If the fraction is sufficiently low, then mixing light sources becomes a good way to solve the problem of color distortion under that particular energy-efficient source.

Along the same lines, some modification of the high-efficiency light sources themselves to improve color rendition is possible. This job has already been started with the advent of such new sources as color-improved HPS. Commonly, improving the color rendering of a given type of light source results in some loss of luminous efficacy. The optimum tradeoff point, either for the modification of a single source, or for mixing two different sources (in a room or similar area), will depend on the relative valuations (weighting) assigned by the user to saving energy and/or money, and to being able to recognize and discriminate colors with accuracy. Accordingly, a full solution to the problem involves determining not a single optimum compromise, but a set of such values, varying with the user-assigned weighting.

6.4 CAPSULE SUMMARY

The results of the preliminary laboratory research suggest strongly that the present safety colors do not adequately convey accurate chromatic information under many of the HID sources. A set of safety colors which appear more universally recognizable have been identified, but further research is suggested to validate this finding. Further research is also needed to determine the feasibility of using these colors on signs in industrial settings.

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APPENDIX A: ADDITIONAL DETAILS OF THE ILLUMINATION IN COLOR LABORATORY

In the Illumination Color Laboratory, illumination could be provided by one of the six different systems. These systems included low pressure sodium (LPS), high pressure sodium (HPS), metal halide (MH), fluorescent (FL), mercury and incandescent tungsten (T). One metal halide, one clear mercury, and one high pressure sodium light was positioned above each of the two lateral sides of the chamber. (Note, clear mercury was not included as a light source in the present experiment.) Each of these lamps was located inside a large, hemispherical aluminum reflector, which was oriented upward at an angle, so as to throw light toward the ceiling of the room, above the chamber itself. This upper ceiling was covered with a specularly reflective material, to reflect the light downward onto the double diffusing ceiling of the illumination chamber. The resulting folded optical path was necessitated by the limited space available within the main room. Shutter panels were placed directly in front of each reflector to control illumination levels. No electronic dimming was used. Two tungsten floodlight lamps were located above the front area of the chamber ceiling, and four were located in the rear. Five fluorescent tubes and eight low pressure sodium lamps, all without reflectors, were located on a motorized carriage, that could be moved into and out of place above the illumination chamber ceiling. To avoid interfering with the light distribution, this carriage was moved out of the chamber when any of the other sources was used.

Three of the walls of the chamber consisted of sheets of painted canvas. Each wall was formed from a large canvas roll painted sequentially in six different colors. Different sections of the roll could be cranked into place, thus permitting wall color and reflectance value to be varied. Although the wall color could be changed to one of six colors, (black, gray, white, red, green, and blue), only black walls were used in the present experiment. The fourth and removable wall panel, constructed of plywood with a black, felt-like fabric surface, contained a 5 in. by 7 in. viewing area for sample presentations. This viewing shutter was covered with the same black fabric, as the rest of the wall panel, when the shutter was closed. During the experiment, the shutter could be raised to expose color samples to be viewed by the observer. Two layers of translucent plastic diffusers formed the chamber ceiling and provided even light distribution. (The floor was covered with gray tile speckled with irregular, light spots.)

APPENDIX B: LIST OF DOCUMENTS COMPLETED DURING THE OSHA/NBS RESEARCH

The following documents and workshops were completed during the course of the OSHA-sponsored project on criteria for signs and color in workplaces.

- Eckerle, K. L., Photometry and Colorimetry of Retroflection: State-of-Measurement-Accuracy-Report, NBS Technical Note 1125, July 1980.

- Kaetzel, L. J., Glass, R. G, and Smith, G. R., A Compter Data Base System for Indexing Research Papers, NBS Technical Note 1123, October 1980, also in Behavior Research Methods and Instrumentation, 12(5), pp. 547-548, 1980.

- Calabrese, J. M., Kaetzel, L. J., Glass, R. G., and Smith, G. R., A Computer Data Base Systm for Indexing Research Papers, NBS Technical Note 1167, October 1967.

- Instrumental Photometric Measurements of Retroflective Materials and Retroflective Devices, Federal Test Method Standard 370, March 1, 1977.

- Fearn, J. E., Durability of Signage on Workplaces: A State of the Art Report with Suggestions for Research, June 19, 1978.

- Billmeyer, F. W., Colorimetry of Fluorescent Specimens: A State-of-the-Art Report, National Bureau of Standards, NBS-GCR 79-185, (NTIS No. PB-80-165-590), October 1979.

- Glass, R. A., Color Perception Under Energy Efficient Lights. Presented at Light, Health, and Design Conference, May 20-22, 1981, Ottawa, Canada. (Sponsored by Health Facilities Design Division, Health Services and Promotion Branch, National Health and Welfare.)

- Center for Building Technology, Special Workshop on Color and Vision in Buildings, December 9, 1980.

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Robert A. Glass, Gerald L. Howett, Karen Lister and Belinda L. Collins

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10. SUPPLEMENTARY NOTES

[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The use of safety-related visual displays such as signs and colors in workplaces is discussed. The discussion includes a review of relevant national and international standards for safety colors and signs. It also includes a review of measures of spatial resolution in human vision, as well as of color sensitivity and color appearance. In addition, research on the effectiveness of safety signs, symbols, and colors is reviewed. Based on the initial literature review, the appearance of safety colors under energy efficient light sources was identified as an area for detailed research. As a result, a laboratory study was conducted in which the color appearance of 45 different color samples under five light sources including energy efficient ones was determined for seven subjects. The color samples were contained in four color series: standard colors; experimental colors; retroreflective and retroreflective-fluorescent colors; and fluorescent-only colors. The results indicated the existence of a set of colors which was more identifiable under all light sources than the current standard safety colors. This set contains a number of fluorescent and retroreflective colors, unlike the current safety colors. Recommendations are made for further research, including field research, to determine the effectiveness of the suggested color set on safety signs under an even broader range of illuminants. The need to assess color appearance under mixed light sources is also addressed.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Chromaticity; color; color appearance; energy-efficient lights; illumination; light source; safety; safety sign; safety symbols; visual acuity; visual sensitivity.

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